Optimization of passive cooling techniques through natural ventilation systems for residential buildings - a literature review.

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I hereby declare that the work submitted is mine and that where I have made use of another's work, I have attributed the source(s) according to the Regulations set in the Student's Handbook.

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Abstract

This dissertation was written as a part of the MSc in Energy Building Design at the International Hellenic University. The main objective of this dissertation is to enlighten the stakeholder that the implementation of passive cooling technique via natural ventilation in residential buildings, located in a Mediterranean climate, can contribute significantly to minimize energy consumption.

In the context of the study, a description of natural ventilation in buildings has been developed and the principles that create it have been studied. The study of natural ventilation has been carried out relative to the contribution of NZEB and EU targets.

Various passive cooling techniques based on natural ventilation have been investigated and their impact individually has been evaluated. Also, different parameters that affect the operation of the techniques, and thus the performance of natural ventilation, has been exhibited in this dissertation.

Energy Plus and CFD simulation are the most used software to simulate and evaluate natural ventilation contribution. Similarities, differences, pros, and cons of their methodologies have been presented. Also, a description of their combination has been conducted.

Finally, various case studies from South EU countries are demonstrated and aggregated to clarify the methodology of Energy Plus that is followed, and the contribution of passive cooling techniques. Moreover, it has been explained for each technique the reason for causing a reduction. The main outcome of the study is how the natural ventilation techniques suggested can be applied in Greece.

To that end, I would like to express my gratitude to my research supervisor, Dr. Ifigeneia Theodoridou for her patience, guidance, supporting and experience throughout the dissertation. Her valuable advice, continuous guidance, and trust were really helpful in order to bring this dissertation to completion.

Finally, I am personally grateful to my family and my friends that constantly supported me to successfully complete my master degree.

Context

1 Introduction
1.1 Impact of building sector

From the beginning of human existence on earth, the provision of a safe and comfortable building was an integral part of his needs. Thus, as humans evolved, the need for a better building has increased since the time spent inside it is also increasing.

Today, the building sector, worldwide, is responsible for 36% of the total energy consumption and 39% of total CO_2 emissions, while for residential buildings the corresponding percentages are 22% and 17% (IEA and UNEP, 2019). At the European level, the proportion of energy consumption for residential buildings is 27% and they are responsible for 40% of carbon dioxide emissions (Bosseboeuf et al., 2015). The corresponding percentages in Greece are 36% for energy consumption and 33% of the emitted CO_2 emissions (Hellenic Republic- Ministry of Environment Energy and Climate Change, 2017). These actions in the building sector have the effect of burdening the environment. Therefore, the need for more energy-efficient buildings has systematically increased in various developing countries in order to achieve the reduction of energy consumption and CO_2 emissions.

1.2 Problem definition

As mentioned above, the need of more efficient buildings is growing alarmingly. In Europe, the EU commission published the EU Directive 2010, which consists the targets until 2020. These targets are the reduction of energy consumption by 20%, the reduction of CO_2 emissions by 20%, and increase the use of renewable energy sources by 20% (EU, 2010). Therefore, the obligation to achieve these goals, it makes necessary to construct buildings with very low energy level of consumption and demand, named as Nearly or Net Zero Energy Buildings. These types of buildings aim to implement efficient design and energy-efficient technologies to reduce energy demand. However, according to the EU Directive 2010, this type of buildings are very high-energy efficient and their required energy is largely covered by renewable energy sources. This means that the use of HVAC system is required, but it must be very efficient. In contrast to a Passive House is a building with very efficient configurations, but the use of HVAC system contributes in a very low degree. The key of its performance is at the usage of designs (Figueira et al., 2014). Its passive designs consist of high efficiency thermal insulation, windows, high levels of airtightness and the use of passive systems such as solar chimney, solar tubes, wind catchers etc. Generally Passive House operates passively and are appears to have better energy performance than NZEB of EU directive (Passive House Institute, 2015) .

Passive techniques, which were mentioned above, are the main key to the high-energy performance of a Passive House. Various types of such techniques are evolved every day in order to improve building energy performance. Natural ventilation is a passive technique, which will be analyzed in this dissertation, appears to be a promising passive technique. Especially, in hot climates indicates positive results in the energy performance of a building and specifically to the reduction of the cooling loads.

It is essential to rethink the design approach of a building and the optimization of the building's needs relative to the natural ventilation technique. A proper design in natural ventilation can provide better air quality in the indoor environment, better thermal comfort, lower maintenance cost, and lower energy consumption to the dwelling.

Regions in South Europe confront the problem of hot summers and because of the climatic changes, this effect appears intensively in nowadays (Heracleous & Michael, 2018). Greece is one of these countries, which will suffer the prolongation of the hot summers. Thus, it is vital to consider the benefits of natural ventilation in Greece. The high frequency of sunny days and wind annually makes natural ventilation favorable. Solar radiation can aid for the buoyance driven and wind benefits the wind driven effect. Both of them are the main principles for the natural ventilation.

1.3 Aim of thesis

The objective of this thesis is to clarify the design approach and the effectiveness of natural ventilation to achieve a possible decrease in the dwelling energy performance at an early stage in Greece. Consequently, this thesis focuses on the acknowledgment of the different parameters that affect a passive cooling strategy and their influence relative to building energy performance.

Passive practices for natural ventilation can help to improve the building balance. Hence, considering the high maintenance cost of mechanical ventilation equipment applied in buildings, the implementation of a passive ventilation system could be profitable. Due to the economic crisis that Greece is experiencing, this application would find many supporters, due to its low maintenance cost. The dissertation focuses on the methodological approach of designing a passive ventilation system in the climatic conditions of Greece. Particularly, the parameters that influence the design approach and the factors an engineer should consider during this early stage are investigated. The way that various factors affect the passive ventilation system itself such as height, width, absorbent surface, etc. is explored. Furthermore, additional factors affecting the passive system are described, such as thermal mass, orientation, window-wall-ratio, surrounding objects, and climate. These factors also have an impact on the energy performance of the building through the passive ventilation system. Finally, this dissertation can be used as a guideline for the improvement of a passive ventilation system and the energy performance of buildings in Greece.

1.4 Scope of thesis

The most well-known strategies for enhancing natural ventilation are presented and evaluated based on the results of various studies. The program, that was used to conduct these results from the surveys, was Energy Plus. In general, the strategies, which were simulated by Energy Plus and assessed about their effectiveness, are cross ventilation, single-sided ventilation, night ventilation, solar chimney, and wind tower. In addition, in each case was considered the factors that affect these strategies and are the followings:

- Thermal mass
- Orientation
- Wall window ratio
- Surroundings
- Climate

Furthermore, an attempt to comprehend the various capabilities that Energy Plus provide compared with the CFD simulation and their combination have occurred. Finally, in the case of the climate of Greece, an assessment is made of the possible application of these passive cooling systems during the summer period in Greek homes.

1.5 Structure of thesis

The dissertation consists of eight chapters. The first introductory chapter describes the aims, the scope, and the structure of the dissertation. Generally, it is important to understand how natural ventilation could be applied to reduce the building's cooling energy consumption. In the second chapter, an attempt is made to describe the condition of residential buildings in Europe and particularly in Greece. Besides, it describes the NZEB, the Passive Houses, and how an application of passive cooling systems can ensure low energy buildings. The third chapter describes natural ventilation in buildings, the phenomenon that exists to create it, and the most widely used passive ventilation systems. The fourth chapter describes the factors that affect natural ventilation and passive cooling techniques from exogenous factors. The fifth chapter describes the programs used to simulate natural ventilation and passive cooling devices. The most popular ones described are Energy Plus and CFD. Moreover, a review of the pros and cons and the possibility of combining them is made. Chapter six describes various case studies that are described according to the methodology of the above programs and the results that conclude. Chapter seven describes how the various passive systems optimize or may worsen their performance as well as the energy performance of the building. Finally, chapter eight describes the conclusions of the dissertation and the final decision on the possible application of natural ventilation as a means of cooling in residential buildings in Greece.

1.6 Literature review – the methodological approach

In order the literature review to be carried out with reliability and clarity to observations, the following methodological approach was followed. The questions that were used as a guideline to the effort to open the path for the research had as an objective to answer fundamental issues and then more complicated states (Figure 1.6.1).

The main questions were: "How natural ventilation can contribute to the building", “What type of principles are used in order to gain natural ventilation benefits”, “Which are the most well-known natural ventilation techniques, “How do they operate generally and specifically on building”. Moreover, throughout the research, more questions were occurred, such as “Which are the factors that affect each technique and how”, “How can be simulated in EnergyPlus and CFD simulation software”, “Which are the differences between these two softwares”, “What type of methodology must be followed for reliable results and what results are carried out in case of combining them”.

A secondary data was used in order to answering these questions and various surveys were read to collect qualities results and evaluate them. The data that was collected derived from Google Scholar research databases. Specifically, the most visited websites were Science Direct and Web of Science, which have data mainly from academic researches.

The main keyword that were used for the research were, “natural ventilation”, “natural ventilation residential buildings”, “natural ventilation wind driven/ buoyance driven”, “cross ventilation”, “Single sided ventilation”, “cross ventilation/single sided ventilation residential building”, “solar chimney”, “solar chimney residential building”, “wind catcher/cooling tower/ evaporative cooling tower”. In addition, other keywords used included the following terms: “natural ventilation surrounding buildings/vegetation”, “window to wall ration natural ventilation”, “natural ventilation Mediterranean climate”, “natural ventilation Greece”, “thermal mass natural ventilation”, “night ventilation” and “orientation natural ventilation”. As for the software EnergyPlus and CFD simulation, the main keywords used were, “EnergyPlus natural ventilation”, “EnergyPlus methodology”, “EnergyPlus natural ventilation residential building”, “CFD simulation natural ventilation”, “CFD simulation cross ventilation/single sided ventilation/surrounding building natural ventilation” and “EnergyPlus and CFD simulation differences”.

The research was restricted to specific weather conditions, mainly Mediterranean climate, the climate in Greece, and other cases similar to them since the main objective of the dissertation was to research the possibility of natural ventilation implementation to Greek residential buildings.

The publications, articles and academic researches identified were assessed based on the outcomes of each research relative on how much the reference building was improved after natural ventilation implementation. The criteria used for the evaluation of the results were in accordance with the improvements of each intervention caused in relation to the energy savings, the internal air velocity and the hours of thermal comfort.

Most of the studies reviewed and finally used to this the dissertation were published during the last decade (2010-2020) and referred mainly to residential buildings. These restrictions were applied choice in order the results to be more reliable and meet with great accuracy the current needs.

Finally, this methodological approach was decided in order to provide the stakeholders with comprehensive information in natural ventilation technique and supply them with the rationality of what an engineer should take into account at the design stage of an understudy building.

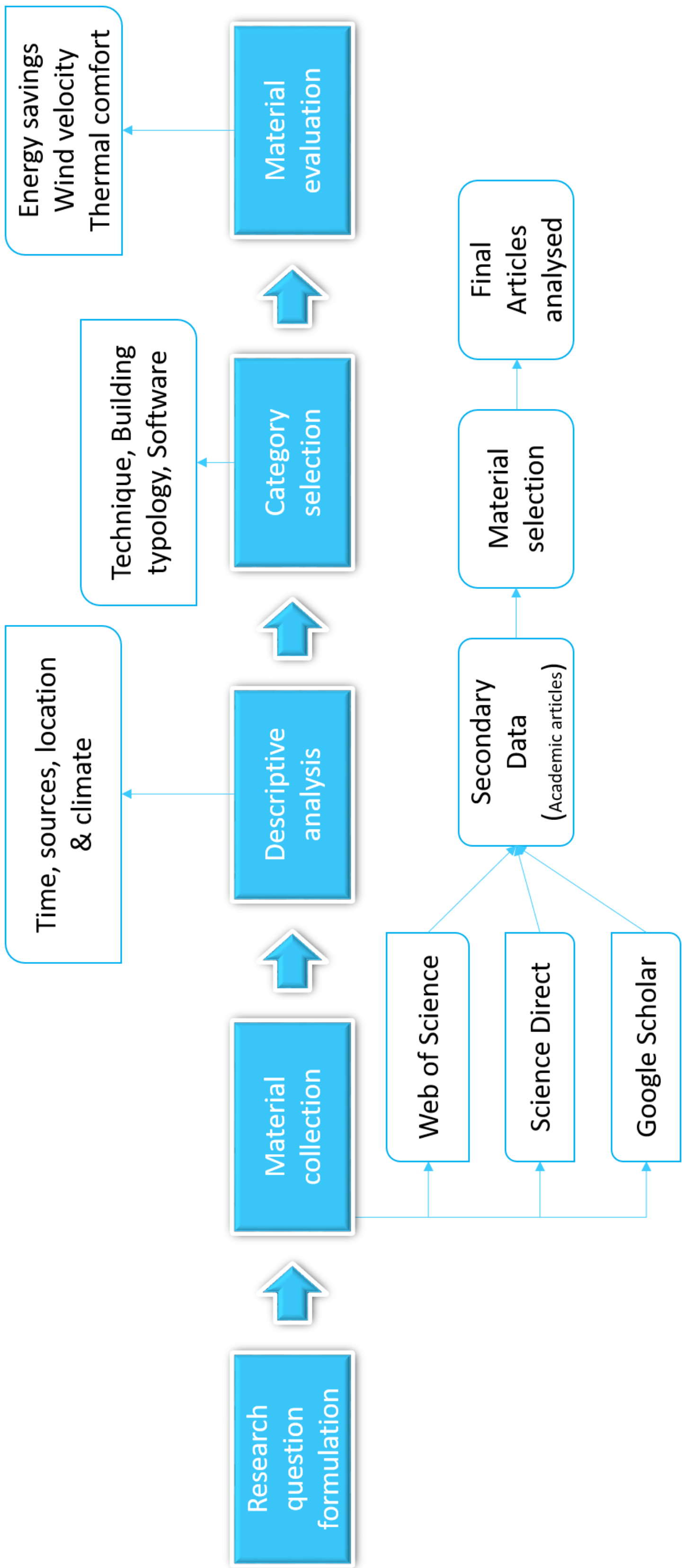


Figure 1.6.1: Methological approach for the literature review

2 Nearly Zero Energy Building

Globally, the building sector has a significant impact on increasing CO2 emissions amount. This increase affects the climate conditions national and at the locally level, which leads to climate change. Almost 39% of the greenhouse gases are directly related to the construction sector emissions (IEA and UNEP, 2019). Moreover, according to Pr. Mat Santamouris, the continued population growth and concertation in large cities, creates higher local urban temperatures (Urban Heat Island), a raise of cooling energy demand, higher degrees of indoor and outdoor thermal comfort, and vulnerable population following by higher levels of mortality (Mat Santamouris, 2016). This is the main problem of the building sector and the European citizens facing. This problem is one of the main reasons, which led the European Commission to take action. The next paragraph describes how the situation in Europe is in building sector from an energy view and what goals they have set to address this problem.

2.1 Europe: Situation today and Goals

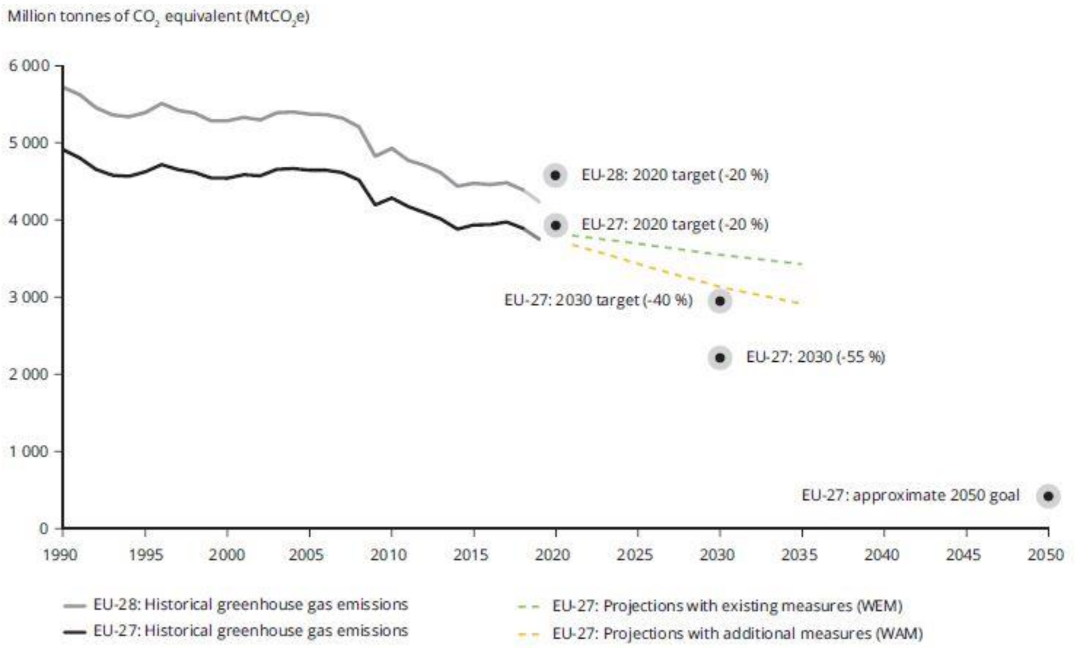
Today, Europe has a significant problem in the building sector, which is responsible for the consumption of approximately 40% of the total primary energy (EU, 2010). Billions of square meters of area have been built and are used for different types of buildings. Thus, more than 70% of that area is used for residential buildings with an average floor space of $87m^2$, and buildings of the tertiary sector cover the rest percentage. The residential buildings are responsible for 27% of the total energy consumption in Europe and tertiary buildings for 14%. According to ODYSSEE and MURE databases, in 2009 European Union countries had buildings with an average energy consumption fluctuating between $150kWh/m^2/y$ and $320kWh/m^2/y$ (Bosseboeuf et al., 2015).

Generally, energy consumption for heating has the highest percentage of energy use (71%) compare to the other energy uses (cooling, lighting, hot water use etc.). As for space cooling represents approximately 10% of the total energy consumption per residential building (Bosseboeuf et al., 2015). The largest percentage comes from Southern European countries, where they experience warmer summers and less cold winter than the North Europe. Therefore, half of these emissions relate to energy consumption for heating and cooling energy demands (Pohoryles et al., 2020). Many householders face extremely serious challenges. One of the most significant challenge is to conserve the proper conditions in their dwellings. They spend enough money only to reach and maintain the thermal comfort of the indoor environment. More and more people can’t afford the maintenance of the housing and live under energy poverty conditions (Mat Santamouris, 2016).

In order to diminish the energy consumption of the building sector and simultaneously the amount of carbon emissions, the European Commission decided to set up and implement specific strategies and policies to tackle the energy poverty. The three principles that Europe determine to follow, until 2020, are the subsequent (EU, 2010):

- Reduction of greenhouse gas (GHG) emissions by 20% compared to 1990
- The 20% of the final energy consumption will be covered by renewable energy sources (RES)
- Increase the energy efficiency by 20%

The first target was succeeded in 2018. In 2018, Europe achieved to decrease greenhouse emissions by 23.2% compare to 1990 levels. In 2019, this target has decreased an extra 3.7%. The next target for GHG emissions is to achieve a reduction of 40% by 2030, 60% by 2040, and 80% by 2050, all these percentages compared to 1990 levels (European Environmental Agency, 2020)**(**Figure 2.1.1**)**



Notes: The calculations of greenhouse gas emission trends, projections and targets include emissions from international aviation and exclude emissions and removals from the land use, land use change and forestry (LULUCF) sector as well as emissions from international navigation.

The 'with existing measures' scenario reflects existing policies and measures, whereas the 'with additional measures' scenario considers the additional effects of planned measures reported by Member States under the Monitoring Mechanism Regulation (EU) 525/2013 (MMR) (?).

The approximate value corresponding to the EU's 2050 goal was derived from those five scenarios exhibiting an emission reduction of 55 % in 2030 compared with 1990 and net-zero emissions by 2050 (i.e. REG, MIX, MIXnonCO2variant, CPRICE, ALLBNK) in the Commission's impact assessment (EC, 2020c). These scenarios take into account technical and natural carbon sinks, resulting from activities such as LULUCF and carbon capture and storage (CCS). As this graph excludes LULUCF emissions and removals, the 55 % value depicted for 2030 should be viewed as an approximation only, while the 2050 net-zero emissions goal translates into positive emissions (EC, 2020c).

Sources: EEA (2020f, 2020j, forthcoming_b), own calculation.

Figure 2.1.1: Target 20% of GHG Source: (European Environmental Agency, 2020)

As for the second target, the EU reached the use of renewable energy, as a proportion of primary energy consumption, at 19.5% in 2019. In 2018, the sector of RES had an upward trend and reached a level of 18.9%. It is much promising that the 20% target will be achieved at the end of 2020. The following target is 2030 with an increase of 32%. The ambitious goals are in 2050, in which the use of RES will reach 100% (European Environmental Agency, 2020). **(**Figure 2.1.2**)**

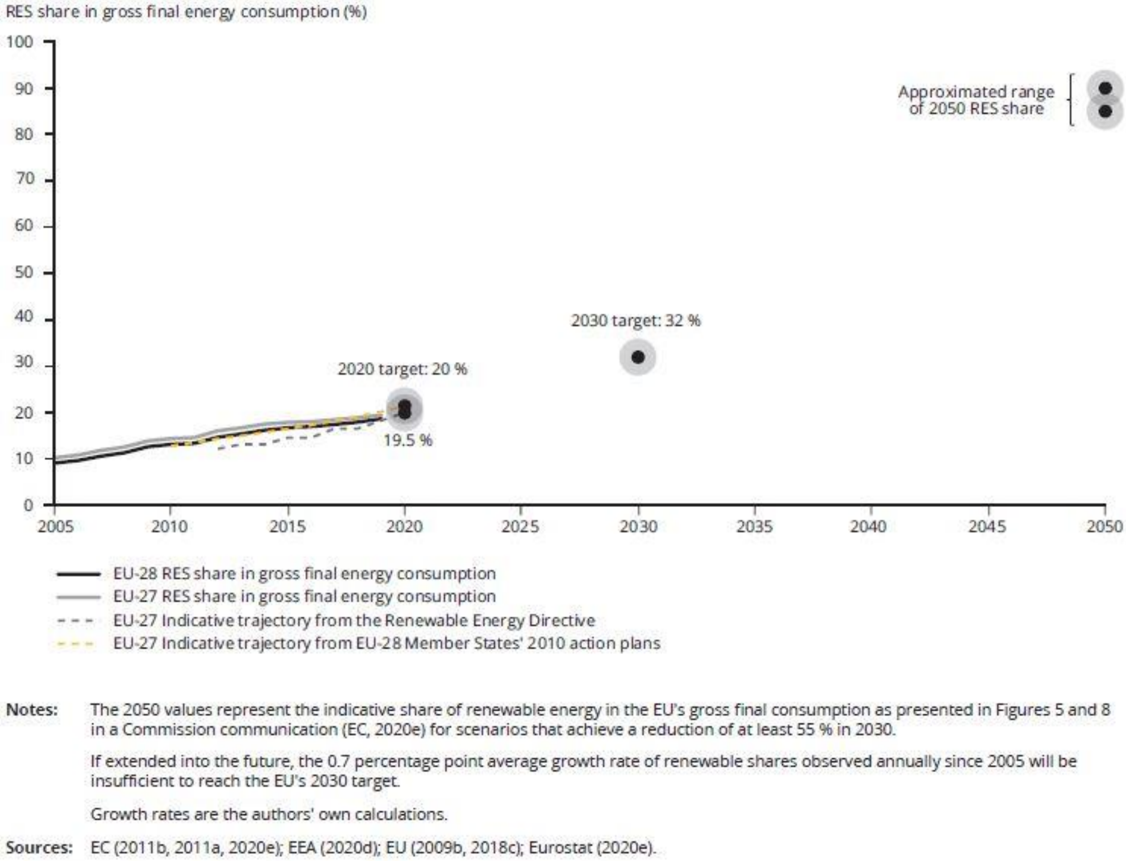
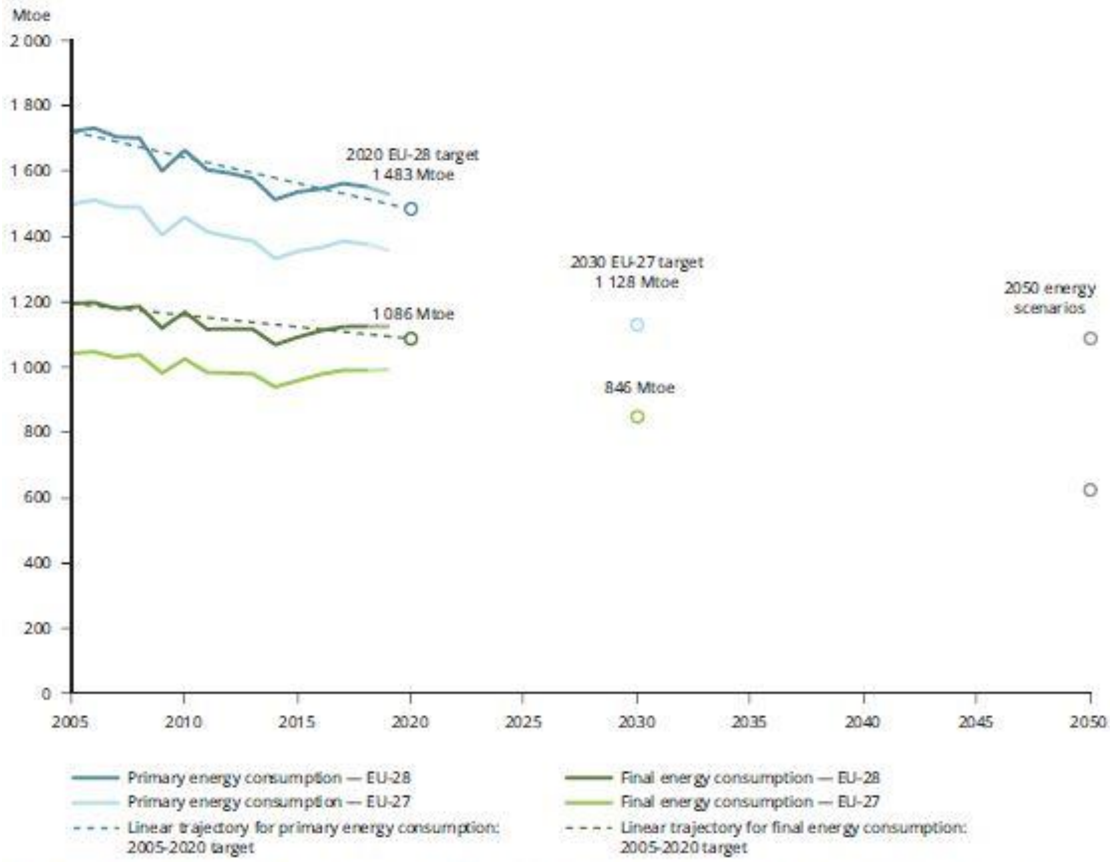


Figure 2.1.2: Target 20% of RES Source:(European Environmental Agency, 2020)

The final target, the EU did not achieve it, because a constant increase of both primary and final energy consumption levels, between 2014 and 2017, deprived the achievement of this goal. In 2019, the reduction that EU members have achieved was 13.8%. Considering that inclination, the next targets of 2030 (1,128Mtoe) and 2050 might be revised (European Environmental Agency, 2020). **(**Figure 2.1.3**)**



Notes: The 2020 EU-28 target represents energy savings of 20 % from levels projected for 2020 in the Commission's 2007 energy baseline scenario (EC, 2008). The EU-27 energy efficiency target for 2030 represents an improved energy efficiency of at least 32.5 % compared with 2030 projections using the same energy baseline scenario. The 2050 values represent indicative scenarios for primary and final energy consumption in the EU-27 that, combined with high shares of energy from renewable sources in the energy mix, would allow the EU to reach a 55 % net GHG reduction by 2030 and carbon neutrality by 2050. The 2050 values are drawn from the GHG reduction scenario MIX assuming medium energy efficiency intensification policies, from the impact assessment accompanying the Commission's recent communication to increase Europe's climate ambition.

Sources: EEA (2020d); EC (2020c); EU (2012, 2018d); Eurostat (2020d, 2020a).

Figure 2.1.3: Target 20% primary energy efficiency Source:(European Environmental Agency, 2020)

2.2 Situation in Greece

Achieving the goals of improving energy efficiency (20%), reducing carbon dioxide emissions (20%), and securing energy supply from renewable energy sources (20%), is done by the contribution of each member of the European Union in its way. Thus, Greece, as a member of the European Union, is taking its steps in achieving the 20% energy savings target by 2020 and further more by 2050.

In Greece, the construction section is responsible approximately for 33% of the CO_2 emissions and consumes about 36% of the total energy consumption (Hellenic Republic- Ministry of Environment Energy and Climate Change, 2017). According to Article 9 of the European Directive 2010/31/EU, it dictates that all newly built buildings should be almost zero energy consumption by 01 January 2021, while for tertiary sector buildings by 01 January 2019. Thus, Greece should deposit a national plan that will include the followings (Hellenic Republic- Ministry of Environment Energy and Climate Change, 2017):

- The determination of technical features of a nearly zero energy building (NZEB), considering the climatic conditions at national, regional or local scale, and an index of primary energy use expressed in $kWh/m^2/a$.
- Milestones for the energy performance improvements of new buildings
- Information on policies and economic or other measures taken to promote buildings with almost zero energy consumption.

The prevailing situation in Greece, according to the census of the building was occurred in 2011 by ELSTAT, the residential buildings represent 79.2% of the total buildings, which means that residential buildings contribute significantly to the national energy-saving strategy. More specifically, the buildings have been built before 1970 represent 41.2% of the residential buildings, and the subsequent buildings, which have been constructed between 1971-1980, constitute 17.2% (Hellenic Republic- Ministry of Environment Energy and Climate Change, 2017) . It is observed that between 2008 and 2011, there was a significant reduction of new building construction because Greece has experienced the national economic crisis until today.

A brief description of what Greece has done so far in terms of legislation will better clarify the current situation. Initially, issued the first Regulation on the Thermal Insulation of Buildings on 1 June 1979, which set out the minimum requirements and measure for the proper thermal insulation. Continuing, Greek legislation had set new measures for the minimization of energy consumption for buildings with the Law 3661/2008. In 2010, a new Law 3851/2010 was published for the promotion of RES integration on buildings. In the same year, approved and established with the K.Y.A. 5825/2010, which was revised in 2017, the Energy Performance of Buildings Directive (EPBD-KENAK). This law inclusive the integration of energy design for buildings to upgrade their energy performance, to succeed energy savings and harmless to the environment (Hellenic Republic- Ministry of Environment Energy and Climate Change, 2017).

Greek Legislation in order to determine at what range the nearly zero energy building would be, the Building Inspection Archive aggregate all energy performance certificates. Running a statistical analysis with sensitivity analysis of the information (degree of confidence: 95%), it was clarified that from 10 to 46 kWh/m^2/year of primary energy for residential buildings are rated as category A+ (Hellenic Republic- Ministry of Environment Energy and Climate Change, 2017) **(**Figure 2.2.1**)**. In this category is more feasible to reach a building to be a nearly zero energy building.

Energy category	**Amounts of energy consumed by residential buildings per climatic zone**			
	A	**B**	**C**	**D**
A+	13 - 28	14 - 29	15 - 46	17 - 36
A	26 - 39	28 - 45	26 - 57	67 - 94
B+	42 - 63	48 - 75	62-103	60 - 118
B	60 - 92	70 - 109	93 - 141	89 - 171

Figure 2.2.1: Energy consumption relative to energy category Source:(Hellenic Republic- Ministry of Environment Energy and Climate Change, 2017)

In the following Figure 2.2.2 shows the limits of the annual primary energy consumption of category A+ for all residential buildings per climatic zones and chronological period. It is observed that for the new buildings the annual primary energy consumption fluctuates between 28kWh/m^2/year and 58kWh/m^2/year (Hellenic Republic- Ministry of Environment Energy and Climate Change, 2017).

Time Period	Climatic Zone	Category maximum A+ (kWh/ m^2.a)	
		Single-family houses	Multi-dwelling buildings
1955-1980	A	35	25
	B	40	28
	C	58	42
	D	56	46
1980-2000	A	50	26
	B	63	29
	C	86	44
	D	94	48
2000-2010	A	50	27
	B	46	30
	C	72	46
	D	87	50
2010-2016	A	34	28
	B	36	31
	C	54	47
	D	58	51
NEW	A	34	28
	B	36	31
	C	54	47
	D	58	51

Figure 2.2.2: Energy performance of new buildings relative to climatic zone Source: (Hellenic Republic- Ministry of Environment Energy and Climate Change, 2017)

Taking into account the above results, the upper limit of the primary energy of a new NZEB is 80 kWh/m^2/year with a minimum contribution of RES at 60% (Hellenic Republic- Ministry of Environment Energy and Climate Change, 2017).

(%)	2005	2010	2015	2020
Residential buildings	15 %	17 %	22 %	27 %
Commercial buildings	10 %	14 %	27 %	39 %
Industrial buildings				
Total	14 %	16 %	24 %	30 %

Figure 2.2.3: Progression of RES use Source:(Hellenic Republic- Ministry of Environment Energy and Climate Change, 2017)

2.3 Definition of NZEB

Relative to the situation that prevails in Europe and especially in Greece, it is proper to refer of what the term of ‘nearly zero energy buildings’ means. According to the Article 2 of the Directive 2010/31/EU, which was integrated into Greek legislation Law 4122/2013, the definition of a ‘nearly zero energy building’ is given. Thus, nearly zero-energy buildings are buildings with very high-energy performance, in which the nearly zero or very low amount of energy required is covered by renewable energy sources to a great extent (D’Agostino & Mazzarella, 2019; Hellenic Republic- Ministry of Environment Energy and Climate Change, 2017; Hemerlink Andreas, Schimschar Sven, Boermans Thomas, Pagliano Lorenzo, Zangheri Paolo, Armani Roberto, Voss Karsten, 2013; Kurnitski et al., 2012; Mariottini & Arcipowska, 2015).

Prior to the attempt of locating the most suitable available roof area for solar panel, or the state of the art equipment for RES, it is rational to minimize the energy performance of the building as much as possible. As D'Agostino and Mazzarella wrote that nZEB allows thermal and electrical requirements to be minimized as much as realistically possible by optimizing the thermal properties of the building structure and increasing the use of solar energy for heating and cooling capacity (D’Agostino & Mazzarella, 2019). In the same line, Dnyandip K. Bhamare, ManishK. Rathod and Jyotirmay Banerjee suggest that it is crucial to develop passive techniques, depending on the building’s needs, which can minimize energy consumption and be more sustainable to provide a satisfactory degree of comfort (Bhamare et al., 2019).

2.4 Passive-House

As the climate changes, it has been observed for the Southern Mediterranean Europe that the average temperature is rising during the summer and in winter also. These changes will have an impact on buildings' cooling and heating loads (Papakostas et al., 2010) Specifically, during the summer (cooling period), the incorporation of passive cooling techniques can contribute significantly to the thermal conditions. Thereby, these techniques can considerably improve the building's indoor environment for human health. Thus, a well-designed passive cooling system like shading openings, insulate building’s envelope, proper vegetation, thermal mass, natural ventilation, the reduction can be achieved (Papakostas et al., 2010). Especially in Greece, which is a country located in Southern Mediterranean Europe.

Passive houses are more desirable in these days because of the high performance that they can achieve with the lowest maintenance cost. In 1991, the Passive House Institute (PHI) of Darmstadt built the first passive house (PH), and it is located at Darmstadt of Germany **(**Figure 2.4.1**)** (Feist & Schnieders, 2009).

Figure 2.4.1: The first passive house building in Darmstadt of Germany Source: (Feist & Schnieders, 2009)

Since then, the concept of passive house paved the way for the NZEB and the contribution of minimizing the CO2 emissions into the environment. PH buildings guarantee to conserve the indoor environment at the thermal comfort levels with the lowest, sometimes not needed, the contribution of the mechanical support system. There are five principles, which define a PH building: guarantee high quality thermal insulation levels, superior windows, very low airtightness level, no thermal bridges, and ventilation system for heat recovery (Figueira et al., 2014).

2.5 Conclusion

The conclusion, according to the above, is that the need to reduce the energy consumption of buildings is essential. Efforts and studies have been made in the past to achieve the reduction of energy demands, such as the passive houses in Germany, Denmark, and other European countries(Feist & Schnieders, 2009; Mariottini & Arcipowska, 2015; Oropeza-Perez & Østergaard, 2014; L. Wang et al., 2009). Passive Houses are the buildings that promise to achieve the goals of European Union, mentioned in previous paragraphs, the NZE buildings (Figueira et al., 2014). The success of low needs for a passive building lies in the use of passive systems. Passive systems (e.g. intergrading shading devices, windows, high-efficiency building insulation, natural ventilation, solar panels etc.) contribute significantly to improve the building's energy consumption. In Europe, the trend of passive systems is growing with the main interest in natural ventilation (Artmann et al., 2007; Ferrante & Cascella, 2011; Gagliano et al., 2016a; Guillén-Lambea et al., 2016). The technique of natural ventilation has many positive results mainly in Southern Europe in both for the energy efficiency of the building and for achieving the thermal comfort of the space. Thus, in the following chapter, the concept of natural ventilation will be analyzed, with which methods it is achieved, how it is affected, and how it is achieved.

3 Natural ventilation

In the previous chapter, it was described in what condition the building sector in Europe and especially in Greece is. Moreover, the Passive House, as it was mentioned, can be the key to provide buildings with low energy requirements. The passive techniques, which are used and especially natural ventilation, are those that contribute to the minimization of the greenhouse gas because they do not need any primary energy to operate. Natural ventilation as a passive technique is a promising technique, let alone in South Europe.

The internal conditions of a building must be at a pleasant level, which means internal air quality (IAQ), temperature and comfort are the main objectives. The demand for mechanical ventilation, in modern houses, increases rapidly and energy implications too. On the other hand, the levels of CO2 emissions increase and as a result drives to an uncomfortable indoor environment. Hence, the interest in natural ventilation exploitation for a high-quality indoor environment has reawakened (Linden, 1999).

Natural ventilation can be created by two phenomena, the wind drive, and the buoyance drive or stack effect. Therefore, natural ventilation uses freely available resources of the wind and thermal energy, the result of solar and incidental heating of the building. As P. F. Linden said "although these resources are free, they are difficult to be controlled" (Linden, 1999). The difficultness of natural ventilation is not only the design stage but also how willing the occupants are to implement each technique. Normally for naturally ventilated buildings, the efficiency depends importantly on the building elements features and how rapidly are influenced by the environment and internal conditions variations. In addition, the occupants' reactions can influence the operation of the technique. Adaptation is another factor that contributes to the efficacy of the dwelling's performance, and so on (Yun et al., 2009)

The most convenient way to control the indoor conditions of a dwelling is through the windows. This action is the most natural and mere technique, which can be applied by any occupant and thus to control the inner environment of the building (Sorgato et al., 2016). Also, there are many others that will be discussed in this dissertation. The disadvantage of this technique requires user interaction. The next paragraphs will be described what natural ventilation means in building and which main techniques lead to natural ventilation.

3.1 Definition of Natural ventilation

The driving of outdoor air through building envelope’s openings into the indoor space by the aid of natural forces creates a phenomenon called natural ventilation. Different types of openings (doors, windows vents), solar chimney, cooling towers, and ducts of aeration are the entries of the natural ventilation. The general purpose of ventilation in buildings is to provide healthy air for breathing by both diluting the pollutants originating in the building and removing the pollutants from it (Atkinson et al., 2009). Natural ventilation possibly, as it will be analyzed in the next chapters, can contribute to the energy saving of a building, as a passive cooling system when the outdoor climate conditions allow it (B. Wang & Malkawi, 2019). Natural ventilation of buildings depends on the climate, building design, and human behavior. The unit that measures the airflow is air change per hour (ACH) and it is used worldwide (Requirements et al., 1981). In most European countries and particularly in Greece, the units that are used the most are m^3/h/person or m^3/h/m^2. (TEE, 2017.Greek Technical Chamber (2017), Technical Directive 20701-1: Analytical national requirements for the parameters entering the calculation of buildings energy performance and the issuing of Energy Certificate. Athens).

3.2 Natural ventilation techniques

Natural ventilation, as it is mentioned, can be created by buoyance driven and/or by wind driven. Each of them can occur independently or simultaneously. Thus, the exploitation of buoyance driven and wind driven can contribute to minimizing energy consumption. During a day, a large amount of heat energy is aggregated and stored in the mass of the element. In this case, the excess energy, which is heat energy, released when the temperature of the element's surface is higher than the indoor temperature of the building. This means that the room or the building will still be heated, even when no heat gains are emitted by the sun. Therefore, this excess energy, either contributes positive (heating period) or must be released to the outdoor environment (cooling period). In other case, the wind direction or velocity can contribute significantly for natural ventilation operation to provide with the optimum conditions in the buildings. The optimum conditions can be a better indoor air quality or temperature or relief materials from excess heat or humidity or combined of all these options and many other factors. In the following paragraphs will be described the wind driven and buoyance driven on how they occur and contribute to the energy performance of the building.

3.2.1 Wind driven

In previous paragraphs, it was described that natural ventilation is created by two factors, the first is wind driven and the second is the buoyance driven. The subject that will be described and analyzed in this section is the wind driven effect.

Wind driven ventilation is a result of various pressures generated on the building envelope by wind. The wind driven effect is occurred by the pressure difference, which is taking place around the building envelope. The positive pressure, or high pressure, is created on the windward side of the building. On the sheltered side of the building, the negative pressure or low pressure is created on the leeward side of the building (Emmerich et al., 2001). Hence, this pressure difference impels the particles of the air to flow within the building from the windward side to the predominant side (Linden, 1999). More simply, the inward direction of airflow to the indoor space through openings is given by the positive pressure difference, and a negative pressure difference drives the airflow out of the building (Asfour, 2015). Hence, the phenomenon called wind driven is occurred by the above procedure (Figure 3.2.1).

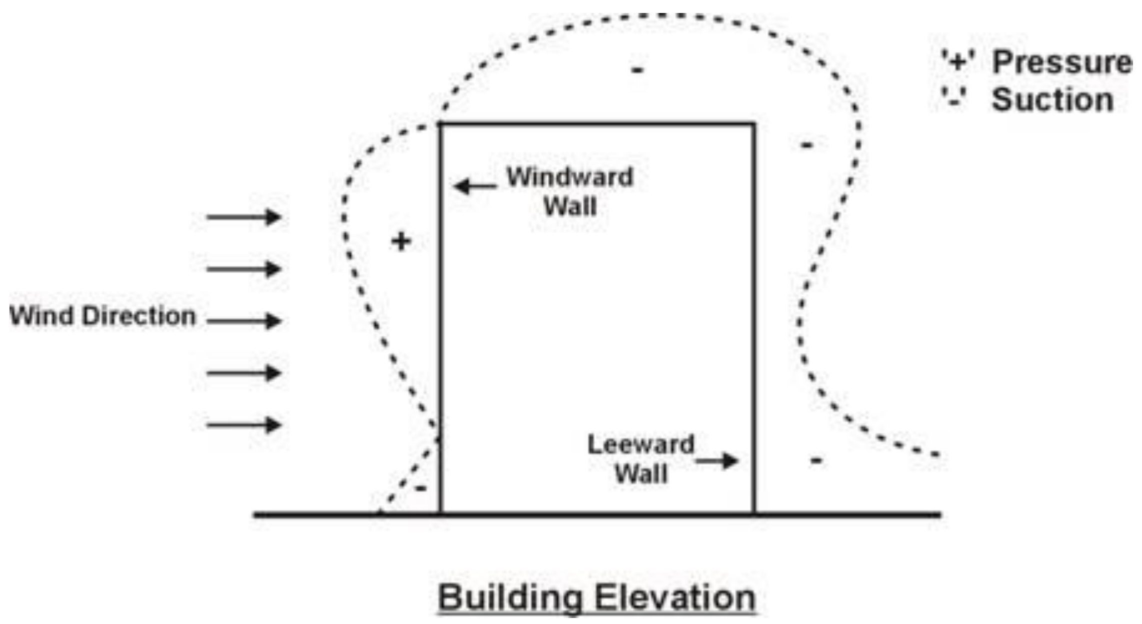


Figure 3.2.1.1: Wind driven sketch Source: https://greenhome.osu.edu/natural-ventilation

The following equation, named as dynamic pressure, gives the wind pressure on a building surface (Asfour, 2015) :

$$p_v = C_p \cdot (1/2 \cdot \rho_u \cdot V_{ref}^2) \text{ [Pa]}$$

Where,

p_v: wind pressure [Pa],

C_p: static pressure coefficient,

V_{ref}: wind speed at reference height [ms^{-1}],

ρ_u: outdoor air density [kgm^{-3}]

The reference height, for the calculation of the static pressure coefficient, is the height that the wind speed is determined simultaneously with the wind pressure level. Usually, the reference height is the height of the building (Asfour, 2015).

Therefore, the equation, which calculates the pressure difference for an opening is the following:

$$\Delta p_j = p_{v,j} - \Delta p_i = C_{p,j} \cdot (1/2 \cdot \rho_u \cdot V_{ref}^2) - \Delta p_i \text{ [Pa]}$$

Where,

Δp_i: static over pressure inside the building

The static over pressure is a parameter, which is affected by the area of the openings in the dominant side and the leeward side.

Many factors affect the pressure difference on each side. Some of them are the building shape, wind direction, and the presence of adjacent buildings or obstacles. These factor will be analyzed in the next chapter.

3.2.2 Buoyance Driven (Stack Effect)

The temperature inside of a building can vary during a period, which can be hours, days weeks or even year. The same applies to the ambient temperature, which changes more rapidly than the indoor temperature because the indoor environment store heat in the mass of the envelope. This storing phenomenon can create differences of the internal and external conditions. This phenomenon called lag. Thus, due to temperature differences occurring between the indoor and outdoor spaces of a building and even between different rooms in the same building create buoyance forces that creates airflow (Kolokotroni et al., 2006). More precise, the difference in the density of the internal and external air creates the thermal buoyance driven ventilation, known as “stack effect” ventilation (Linden, 1999).

Hot air, as natural tendency, flows upward and concentrates at the top section of the space. This movement is occurred because dilute air (hot air) is lighter than the dense air (cold air). The difference pressure, in this case, is occurred by the difference in density, and thus the air is pulled in and out of a space or buildings through special designed openings in the building envelope (Allocca et al., 2003; Z. Zhai et al., 2011).

This is the reason, that in most cases the outlet openings are near the top of the space and the inlet openings are near the bottom of the space (Asfour, 2015) (Figure 3.2.2).

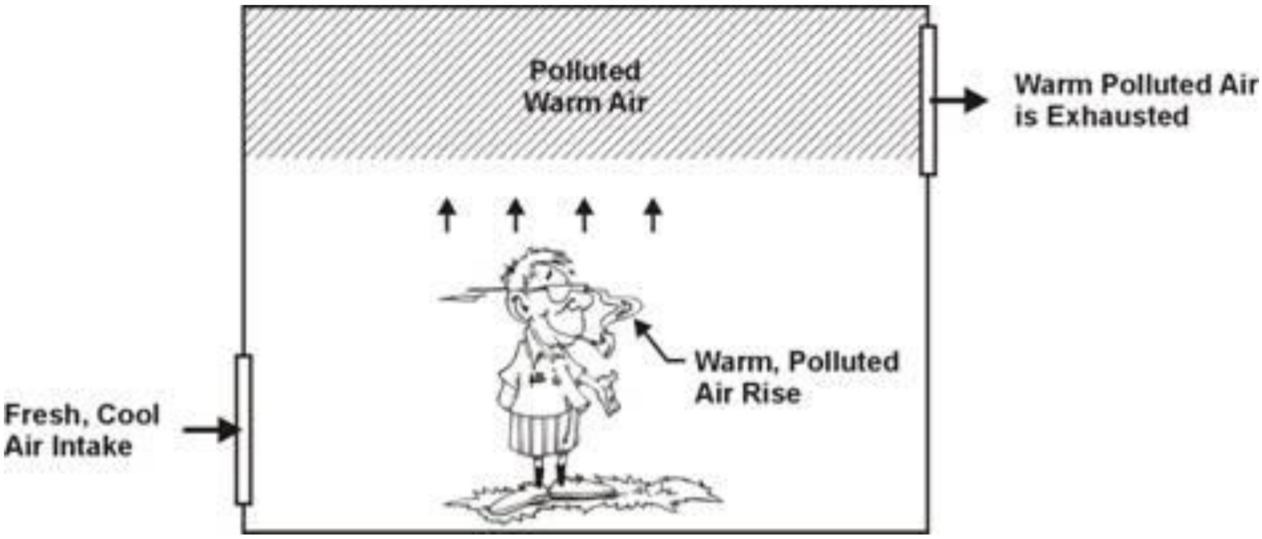


Figure 3.2.2.1: Stack effect sketch Source: https://greenhome.osu.edu/natural-ventilation

According to Tommy Kleiven an opening which located in a height h relative to the top of the floor plan, the difference pressure is given by (Asfour, 2015):

$$\Delta p_h = \rho_u \cdot g \cdot (h_0 - h) \cdot \Delta T/T_i = \rho_i \cdot g \cdot (h_0 - h) \cdot \Delta T/T_u \text{ [Pa]}$$

Where,

Δp_h: pressure difference [Pa],

ρ_i, ρ_i: inside and outside air density respectively [kgm^{-3}]

g: gravity acceleration [ms^{-2}],

h_0: vertical distance between the floor plan and the neutral plane [m],

ΔT: temperature difference between external and internal air [K],

T_i, T_u: inside and outside temperature respectively [K].

Thus, for an inner space with two openings plus the pressure difference over the lower and upper openings respectively, the total driving pressure is given by (Asfour, 2015):

$$\Delta p_{total} = \rho_u \cdot g \cdot (h_2 - h_1) \cdot \Delta T/T_i = \rho_i \cdot g \cdot (h_2 - h_1) \cdot \Delta T/T_u \text{ [Pa]}$$

$$\Delta p_1 = \rho_u \cdot g \cdot (h_0 - h_1) \cdot \Delta T/T_i = \rho_i \cdot g \cdot (h_0 - h_1) \cdot \Delta T/T_u \text{ [Pa]}$$

$$\Delta p_2 = \rho_u \cdot g \cdot (h_0 - h_2) \cdot \Delta T/T_i = \rho_i \cdot g \cdot (h_0 - h_2) \cdot \Delta T/T_u \text{ [Pa]}$$

Where,

Δp_{total} : total driving pressure [Pa]

Δp_1, Δp_2: pressure difference over the lower and upper opening respectively [Pa]

h_1, h_2: vertical distance between the floor plan and the lower and upper opening respectively [m].

Depending the results of the pressure difference Δp_1 and Δp_2 gives the direction of the airflow. For instance if $\Delta p_i > 0$ means that the air penetrates into the room and vice versa for negative Δp_i. The equation that gives the location of the neutral plane is the following (Asfour, 2015) (Figure 3.2.):

$$h_0 = \frac{A_1^2 \cdot h_1 + A_2^2 \cdot h_2}{A_1^2 + A_2^2} \text{ [m]}$$

Where,

A_1, A_2 : area of the lower and upper opening respectively [m^2].

As it is obvious, the factors that affect the phenomenon are the building shape, solar radiation, the surface (solar absorption) and climatic conditions.

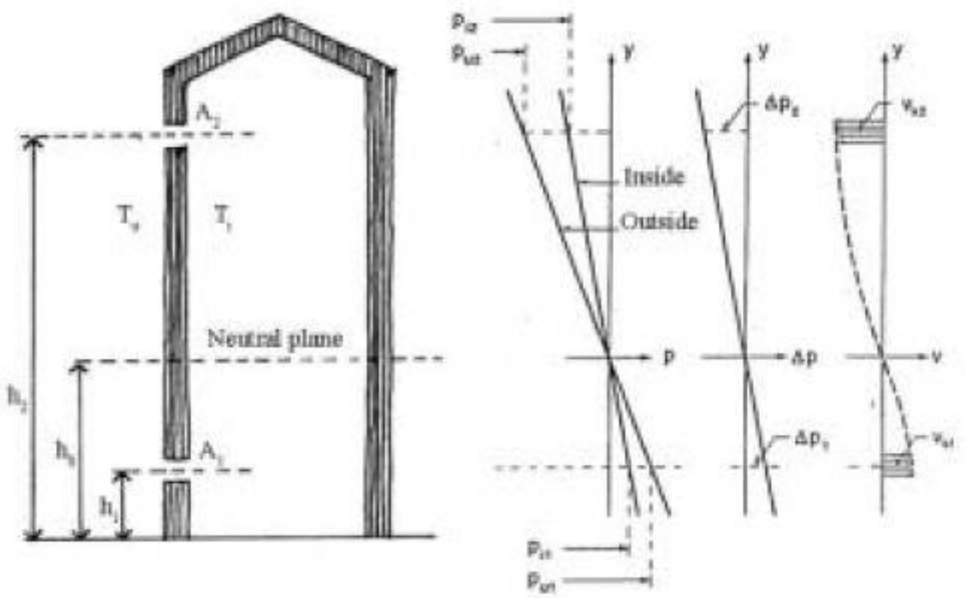


Figure 3.2.2.2: Thermal buoyancy between two openings Source:(Asfour, 2015)

The buoyancy driven phenomenon, as discussed above, depends solely on the temperature difference and its stratification between the outdoor environment and the indoor space. As a result, it is affected by the climate, by the sun's radiation, the shading (surrounding buildings or shading systems or vegetation) and the building's ability to store heat (Asfour, 2015). Therefore, it is essential to take the advantage of this phenomenon in order to ventilate the interior space of a building.

3.2.3 Conclusion

In previous paragraphs were explained the phenomena of wind driven and buoyancy driven. These two phenomena are created in different ways and are influenced by different factors, but both cause air movement. In fact, both phenomena occur simultaneously. The percentage that happens each depends on the prevailing conditions, according to those mentioned above. What an engineer is called upon to design is to be able to tame these two driving forces to take advantage of them. Wind driven, according to Ben Richard Hughes and Mak Cheuk Ming, is more effective phenomenon compare with buoyance driven (Hughes & Mak, 2011). Thus, the next subsection will analyze and describe the most common passive techniques that use these phenomena to enhance natural ventilation indoors.

3.3 Passive natural ventilation strategies

Wind driven and buoyance driven are the phenomena that makes the air to flow through a space. Both of them need special treatment in order to achieve an adequate air movement and thus better natural ventilation. Strategies that can enhance the airflow rate by taking the advantage of these mentioned above phenomena are many. In this subchapter will be described the most used strategies to achieve a thermal comfort in the indoor space.

It is usually possible to separate natural ventilation into two types: organized natural ventilation and unorganized natural ventilation (Zha et al., 2017a). The driving of the indoor air to the outdoor ambient through outlet devices at the ducts of the building is called organized ventilation. Generally, organized ventilation is the way to control the airflow more efficiently. On the other hand, penetration of uncontrolled air by the means of leaks and cracks in structures, known as infiltration, and by ventilating the building through the fenestrations and vents is the unorganized ventilation (Zha et al., 2017a).

Unorganized ventilation techniques allowing the air to flow freely inside the building with only inlet and outlet are windows and vents. Some of these techniques, which will be presented in this dissertation are:

- Cross ventilation
- Single sided ventilation
- Night ventilation

Organized ventilation techniques allowing air to flow more controlled and certain circumstances through well-designed routes. The techniques, which are used for the organized ventilation and will be presented later in this dissertation, are:

- Solar chimney
- Wind tower

3.3.1 Cross ventilation

Cross ventilation is one of the most used natural ventilation techniques. Cross ventilation is occurred by the synergy of two or more openings on two opposite sides of the building. Usually, ventilation air comes in and out through windows, hatchers, grills or special designed openings integrated into the façade. Thus, the ventilation air moves from the dominant side to the leeward side of the building (Asfour, 2015; Emmerich et al., 2001; Geros et al., 2005; Ohba & Lun, 2010; Visagavel & Srinivasan, 2009). The wind-driven forces are the dominant phenomenon in the cross-ventilation technique. More precisely, the wind induces positive pressure on the windward surface and on the opposite side induces negative pressure. Therefore the opening which is under positive pressure allows the inward acting and on the opposite side, the under negative pressure opening acts as an outlet area (Mat Santamouris & Wouters, 2006).(Figure 3.3.1)

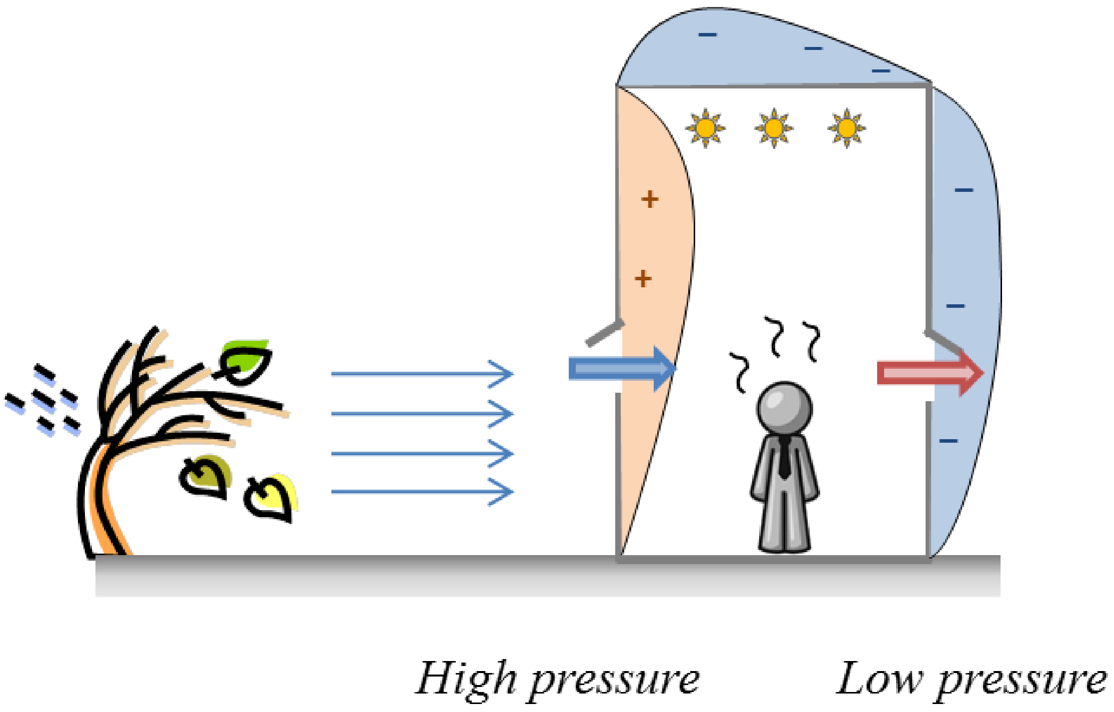


Figure 3.3.1.1: Wind drive cross ventilation Source: http://coolvent.mit.edu/intro-to-natural-ventilation/basics-of-natural-ventilation/

3.3.2 Single sided ventilation

Single sided ventilation is used mostly in spaces that have openings area on one side. For instance a flat of a multifamily building in most case has one side openings. Thus, it is important to be studied to find solutions on how these spaces can be ventilated naturally. Firstly, it is significant to examine how this strategy works and which natural ventilation technique prevails.

According to N.C. Daish and et al. the single sided ventilation strategy can be separated into two types. The first type, the dominant façade accommodates only one opening on its surface, thus the outdoor air penetrates the room and the indoor are being removed both through the same opening. In the latter type, the inlet and outlet areas are divided. Therefore, the air can enter and escape from different opening. It is obvious that the former case does not have the ability to ventilate a room such easy as the second case (Daish et al., 2016).

The location of ventilation openings determines the temperature or/and pressure difference within a space. In the case of single opening, the larger the area the better efficiency of single sided ventilation is. As for the cases where ventilation openings are two or more, the efficiency can be determined by the different height between them and the ventilation rate can be enhanced by stack effect or wind driven effect. Hence, the buoyance driven can be more efficient if the vertical distance between two openings increase or the temperature difference between ambient and interior space becomes greater (Asfour, 2015; Daish et al., 2016; Mat Santamouris & Wouters, 2006). Single sided ventilation appears to generate lower ventilation rates and ventilation air does not penetrate deeply into the space (Daish et al., 2016). (Figure 3.3.2and Figure 3.3.)

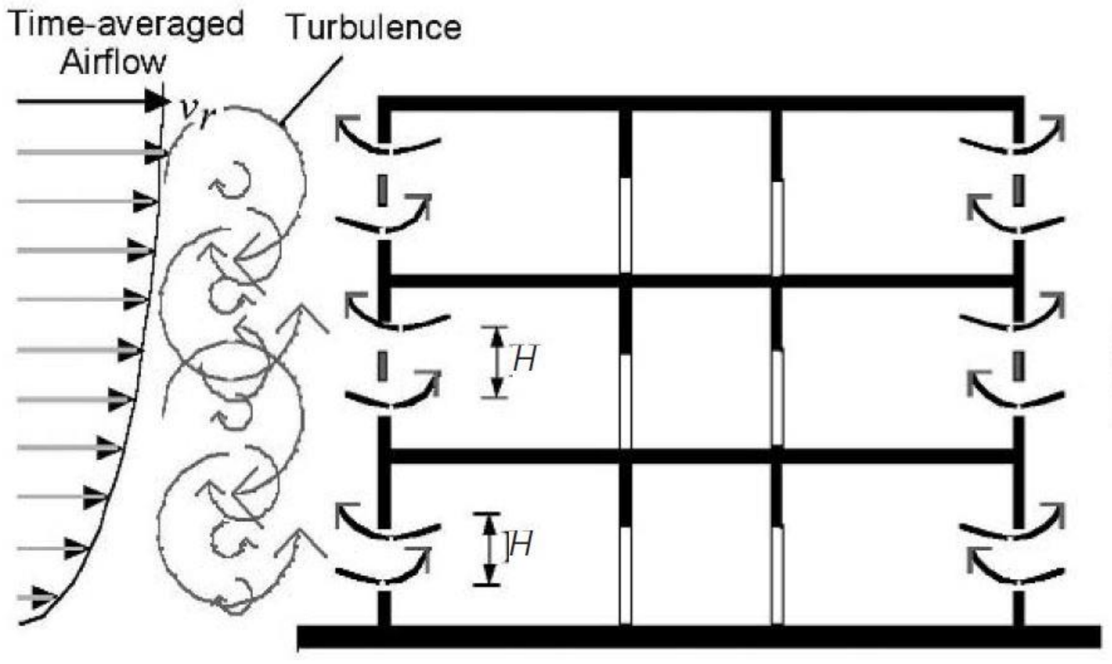


Figure 3.3.2.1: Different types of single sided ventilation Source: (Mat Santamouris & Wouters, 2006)

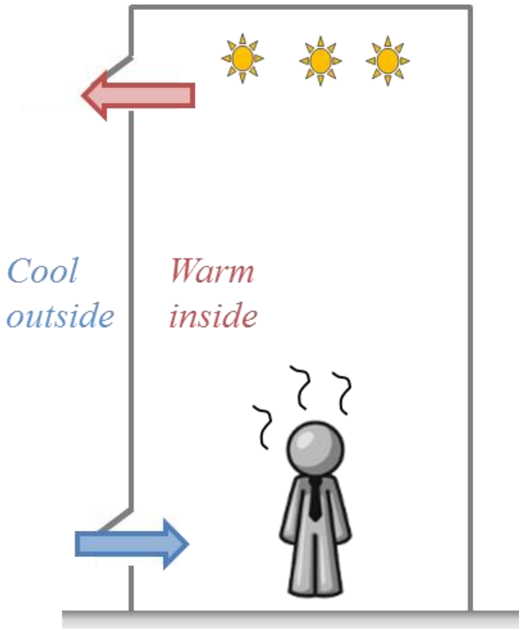


Figure 3.3.2.1: Single sided ventilation. Source: http://coolvent.mit.edu/intro-to-natural-ventilation/basics-of-natural-ventilation/

3.3.3 Night ventilation

The global climate change is caused by numerous human activities worldwide and in different scales and sections. One of these sections, which contributes negatively to climate change, is the urban heat island phenomenon in urban places. Urban heat island provokes increases of the ambient temperature and as a result, prolongation of hot periods and the heat waves occur more frequently. These changes have an impact on indoor temperature. Furthermore, the energy demand for cooling becomes greater (Geros et al., 2005; M. Santamouris et al., 2010). Therefore, it is essential to invent other techniques for cooling the indoor environment in summer periods. Relying on Livada, Santamouris, and Assimakopoulos research the demand for A/C in the global market was increased by 300% and the correlated section in Greece was increased by 800% (Livada et al., 2007).

The above researches denote that the demand for passive cooling techniques becomes more intense. Night ventilation is one of the cheapest passive cooling techniques. This technique can contribute to restraining the cooling load of building at a low level, and maintain the indoor conditions at a thermal comfort level (Kubota et al., 2009).

In summer periods, most of the days, outdoor temperature exceeds the temperature of which occupants feel comfortable, so the daytime ventilation in these cases do not aid to conserve thermal comfort conditions (Pesic et al., 2018) The thermal mass of the building’s elements play a major role in the performance of night ventilation. During the day, the elements absorb heat energy through the air (via conduction) and/or solar radiation form (via radiation) and moderate the increase of indoor temperature. Thus, the indoor air temperature will delay exceeding the thermostat cooling set point of the HVAC. Averted in this way the extra hours of use of the HVAC system (Springer et al., 2005) The question is what happens if the thermal mass of the elements saturates and the temperature of the indoor space is lower. In this case, the elements initiate to emit all these heat gains back to the environment. Therefore, an unwanted increase in temperature will occur at nighttime and the occupants will feel uncomfortable. On the contrary, ventilating the space during night, known as night ventilation or night flushing, will aid to tackle this problem. All openings are opened during the night times. In this period of the day the outdoor temperature, in most cases, is lower than the indoor temperature. The technique's efficiency is dependent primarily on the relative temperature difference between the outdoor and indoor environment during the nighttime (Axley, 2001; M. Santamouris et al., 2010).

A survey carried out in China, about an office building, showed that the maximum temperature of the thermal mass at daytime occurs in the afternoon time. At nighttime, the heat release starts and the minimum temperature occurs at midnight (L. Yang & Li, 2008). Night ventilation is a significant factor and can be key to minimizing the cooling loads of building's demands (Kolokotroni et al., 2006). Another study with the title "Natural ventilation for cooling in Mediterranean climate: A case study in the vernacular architecture of Cyprus", in which researchers examine the best option to reduce the cooling loads for a traditional settlement of Kapedes, they conclude that night ventilation can have a positive impact on building's energy performance. Night ventilation indicates that is the most efficient cooling strategy compared to daytime and full-day ventilation (Michael et al., 2017).

Hence, according to Mat Sanatamouris and Peter Wouters the indoor conditions are affected by night ventilation relative to the next day in four ways (Mat Santamouris & Wouters, 2006) (Figure 3.3.):

- Reducing the highest air temperature
- Reducing air temperature during morning hours, when occupants occupy the space
- Lowering slab temperature
- The time lag increases

In the same survey, they conclude that night ventilation depends upon the following parameters:

- During the night time, the temperature and atmospheric air circulation throughout the building
- The efficiency of the flow of heat between the air in circulation and the heat mass
- The thermal storage of the elements.

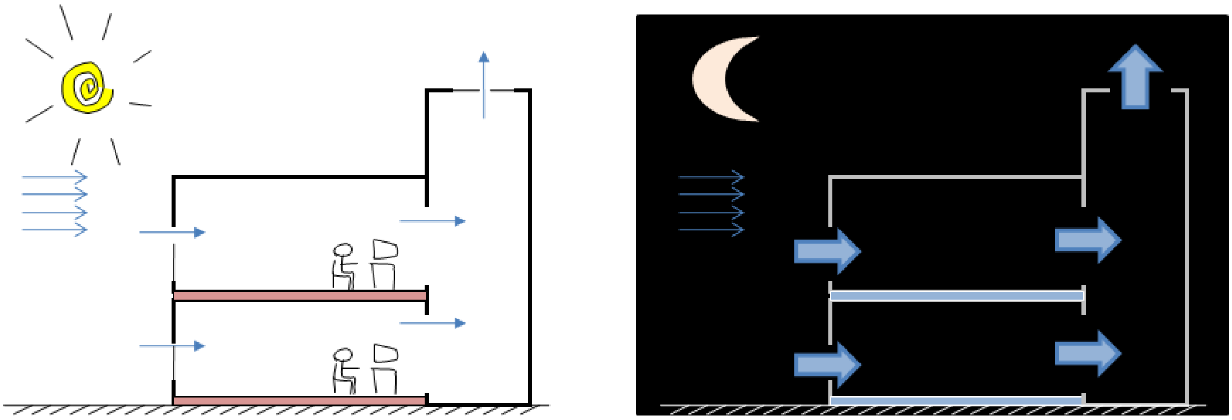


Figure 3.3.3.1: Night ventilation Source:http://coolvent.mit.edu/intro-to-natural-ventilation/basics-of-natural-ventilation/

3.3.4 Solar Chimney

Solar chimney, as an organized type of natural ventilation, has been implemented widely on Passive Houses. In recent years, the solar chimney has been the object of study by many researchers and is now attracting the interest of more and more designers, who searching for effective passive solutions. Solar chimney can be designed for either power generator or enhancing natural ventilation ability of the building (Layeni et al., 2020). This dissertation assesses solar chimney as a passive ventilation system.

It is a passive cooling technique, which has been extensively studied to provide buildings with natural ventilation (Koronaki, 2013; Lee & Strand, 2009; Neves et al., 2011; Shi et al., 2018; A. Y. K. Tan & Wong, 2012; Zha et al., 2017b; G. Zhang & Shi, 2018). The integration of this ventilation system requires the junction of solar radiation (Mat Santamouris & Wouters, 2006). A solar chimney is a passive system with high thermal mass, which utilizes solar energy to generate buoyancy force to drive out the indoor air to the environment and through other inlets, air replenished with fresh air. An implementation of this passive system is expected to enhance the air velocity of natural ventilation and cause a reduction in the use of mechanical ventilation (Hong et al., 2019). Many factors can influence a solar chimney's performance, and each of them affects the performance differently. Based on Long Shi, Guomin Zhang, Wei Yang, Dongmei Huang, Xudong Cheng, and Sujeeva Setunge's research (Shi et al., 2018), they conclude that there are eight influencing factors. These factors including inclination angle (if it is structured tilt), cavity gap or width, height, the relationship between height and gap, inlet area, outlet area, the ration between inlet and outlet, and finally solar radiation. All of these factors are relevant to the construction of the system, except the last one that is affected by not only the solar chimney structure, but the climatic conditions also. Another factor is the orientation of the chimney, countries located above the equator south orientation provides the best performance (Koronaki, 2013).

It is important for the designer of a solar chimney to consider many factors to comprehend, implement and achieve the highest performance of natural ventilation. The answer to the question of which factor is most influential on the efficiency of the solar chimney cannot be unilateral. For example, there is research that had been run simulations and conclude that as the gap increases between the absorber and glass cover the airflow increases too (Mathur et al., 2006). While in another research showed that an increase of chimney's height from the inlet area improves the efficiency of the solar chimney

(Layeni et al., 2020). However, there is unanimity in all research that the amount of solar radiation is the one that greatly affects the chimney's performance (Figure 3.3.4.1, Figure 3.3. and Figure 3.3.).

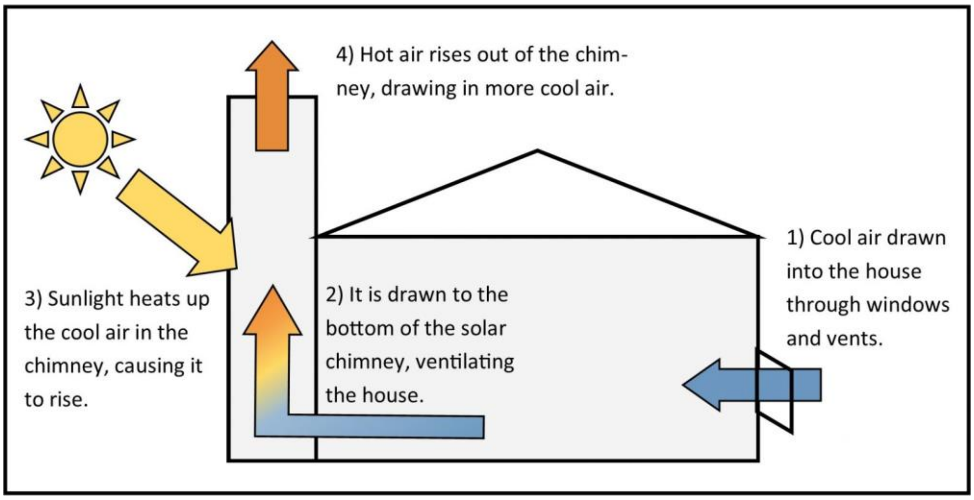


Figure 3.3.4.1: Solar chimney air circulation
Source:http://www.yougen.co.uk/i/uploads/gallery/Solar%20Chimney%20.jpg

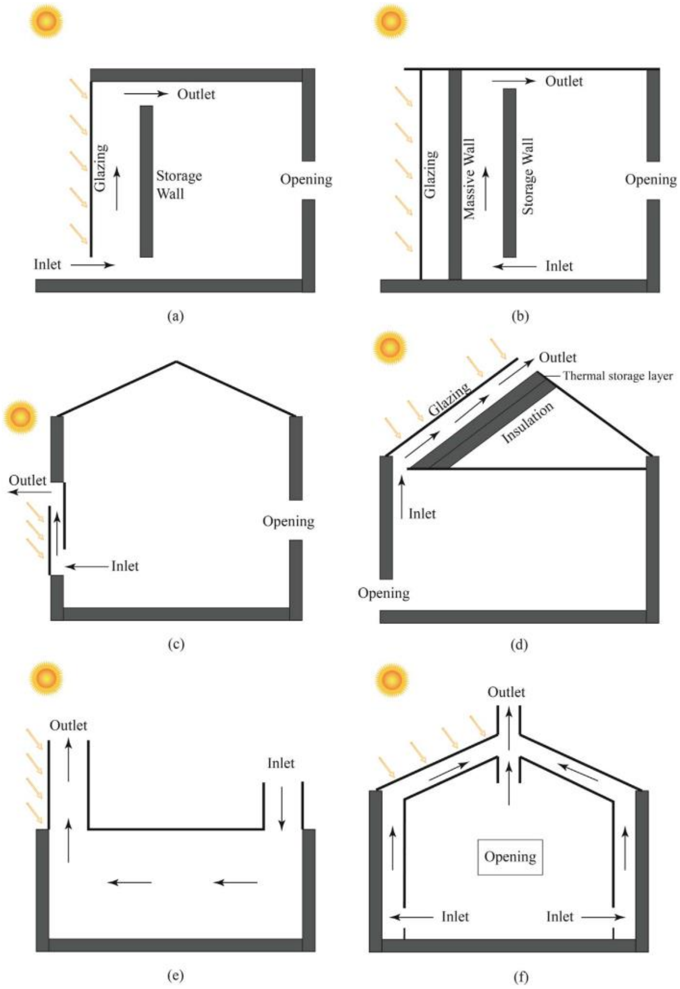


Figure 3.3.4.2: Different type of solar chimney Source:(Shi et al., 2018)

Figure 3.3.4.3: Solar chimney Source:(Zha et al., 2017b)

3.3.5 Wind tower

Demanding to conserve thermal comfort in the residential section depends on various parameters, like the wall window ratio, insulating standards, shading devices, airtightness of buildings envelope, thermal mass, occupants' activities, and climatic conditions.(Babich et al., 2017). Climatic changes and the altitude of the region affect all these parameters also. South Europe has a warmer and drier climate following by longer summers, less precipitation, and greater solar gains. Thus, the demand for integrating passive cooling techniques increases.

Wind tower can be defined as the way to make the "job" for natural ventilation easier and efficient (Hughes et al., 2012; Hamid Montazeri, n.d.). Wind tower was implemented on buildings' envelopes, like a solar chimney, and the architecture design originated from the Middle East back to the fourth millennium BC (Ghaemmaghami & Mahmoudi, 2005). Due to the hot arid regions of Iran and Persian countries, citizens in those countries had the demand to cool their buildings. A wind tower is known as wind catcher and in the Middle East region as "Baud- Geer" or "Bagdir" or "Malkaf" and "Malaaqef" (Bahadori, 1985, 1994a; H. Montazeri & Azizian, 2008; Varela-Boydo & Moya, 2020; Yaghoubi et al., 1991). Today, it gains more followers to apply this passive cooling system on their buildings to reduce the energy demand (Hughes et al., 2012). The application of wind catcher shows that humans and the environment can harmonize and cease to "harm" each other (Ghaemmaghami & Mahmoudi, 2005).

The wind catcher takes the advantage of two driving forces: the pressure differences (wind driven) on the perimeter of the building's envelope and the temperature differences (buoyancy driven or stack effect) depending on the thermal mass, solar radiation, evaporative cooling, and other parameters conduce to the phenomenon to be achieved (Hughes & Mak, 2011). The first driving force, wind driven, occurs when there is the wind in the area. Then the tower "catches" the wind and the air is pushed through the openings in the bottom level of the tower and through it to the rest building space, depending on which windows and doors are opened at the negative pressure side (Hughes & Mak, 2011; Yaghoubi et al., 1991). It is important that the tower should be positioned in a place to enhance the wind driving forces between the inlet and outlet surfaces. According to Hughes and Ghani, the air pressure can be changed easily to improve the thermal comfort of the indoor environment (Bahadori, 1994b; Hughes & Ghani, 2010)

The second driving force, which is the temperature differential, is applied when there is very low wind velocity or the absence of it. In this case, the wind tower works as exhaust by driving the sparse air masses (warm air) rise up and denser air masses (cold air) initiates enter in the inhabitant space(Ghaemmaghami & Mahmoudi, 2005; Hughes et al., 2012; Hughes & Mak, 2011). It works like solar chimney.

Another ability that wind towers have and make them special is the potential of evaporative cooling. It is a hybrid technique, which applies a mechanical system to provide the tower with a moist and the passive technique which is temperature differential. Therefore, as the air has a dry bulb temperature when it absorbs water vapors, it gains a wet-bulb temperature. The wet-bulb temperature reaches lower degrees than the dry bulb and the temperature difference can reach more than 2^{o}C (Babich et al., 2017; Mat Santamouris & Wouters, 2006). Thus, the air flows downward through the tower, exits from the bottom of it, and then continues to the rest building space. The evaporative technique is integrated with the next solutions (Hughes et al., 2012; Varela-Boydo & Moya, 2020) (Figure 3.3.5.1):

- Wetted columns inside the tower's duct, which cools the hot dry outdoor air before introduced in the building. Clay conduits or cloth curtains equip wetted columns, hanging vertical and have space between each other 5-10cm. Works better with high air velocity.
- The wetted surface works the same with the wetted column, but the difference is that they are equipped with evaporating cooling pads at the inlet area of the wind catcher. These devices wetting the top of it. Works better with low air velocity.
- Another type is the use of underground channels. The wind tower facing the leeward side, so negative pressure prevails. Then the cool air from the underground channels rises up, because of the buoyance drive effect, and distributed to all rooms and then exits from the under-pressure side. Then hot fresh air replaces the cool air, and because of latent energy, the hot air becomes cooler and then follows the above procedure

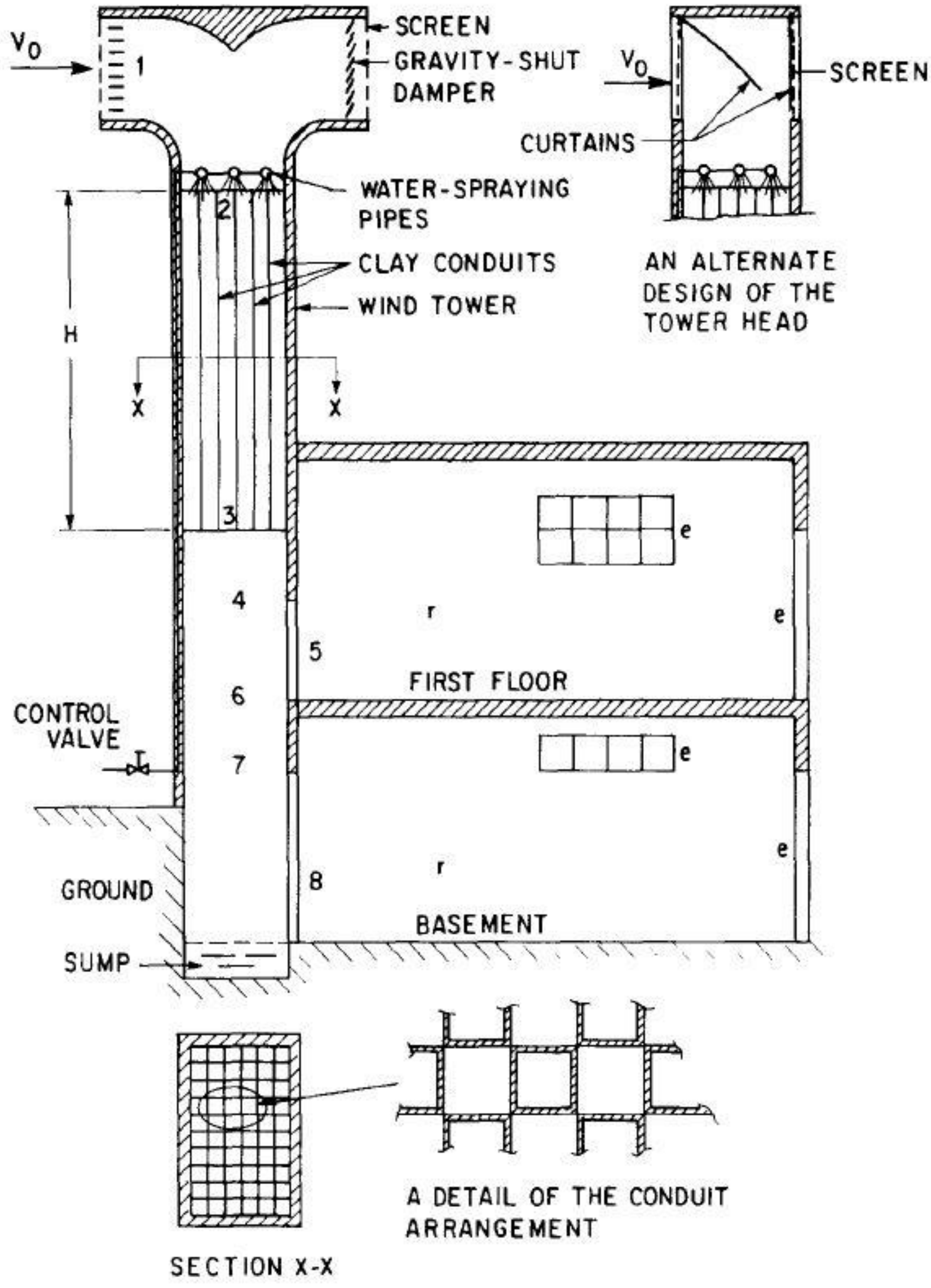


Figure 3.3.5.1: Evaporative cooling mechanism Source:(Bahadori, 1985)

The last function of the wind tower is the night flushing. At nights, the ambient temperature drops significantly and the cool air is heavier than hot air. Hence, the cool air penetrates the building through the wind tower and replace the hot air, which exits from the openings. This phenomenon continuous until the stored heat from the thermal mass of the elements vanishes or until the next morning (Hughes et al., 2012). **(**Figure 3.3.**)**

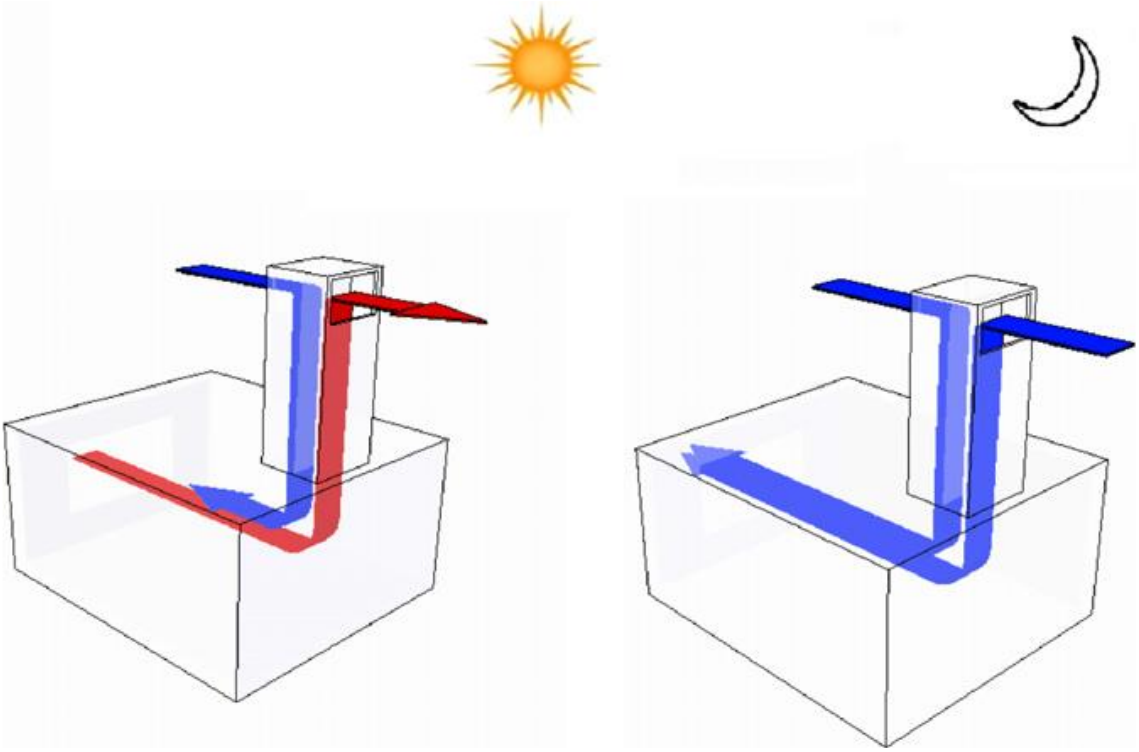


Figure 3.3.5.2: Comparing the function of a wind tower during day and night Source: (Hughes et al., 2012)

Wind towers can be classified by the numbers of their openings. There are one-sided, two-sided, four-sided, six-sided, eight-sided, and twelve-sided wind catchers. The selection of the design is related to wind direction and velocity. Each of them has its pros and cons, but the most used sided are one and fourth (H. Montazeri & Azizian, 2008; Hamid Montazeri, 2011; Varela-Boydo & Moya, 2020)(Figure 3.3.5.33**)**.

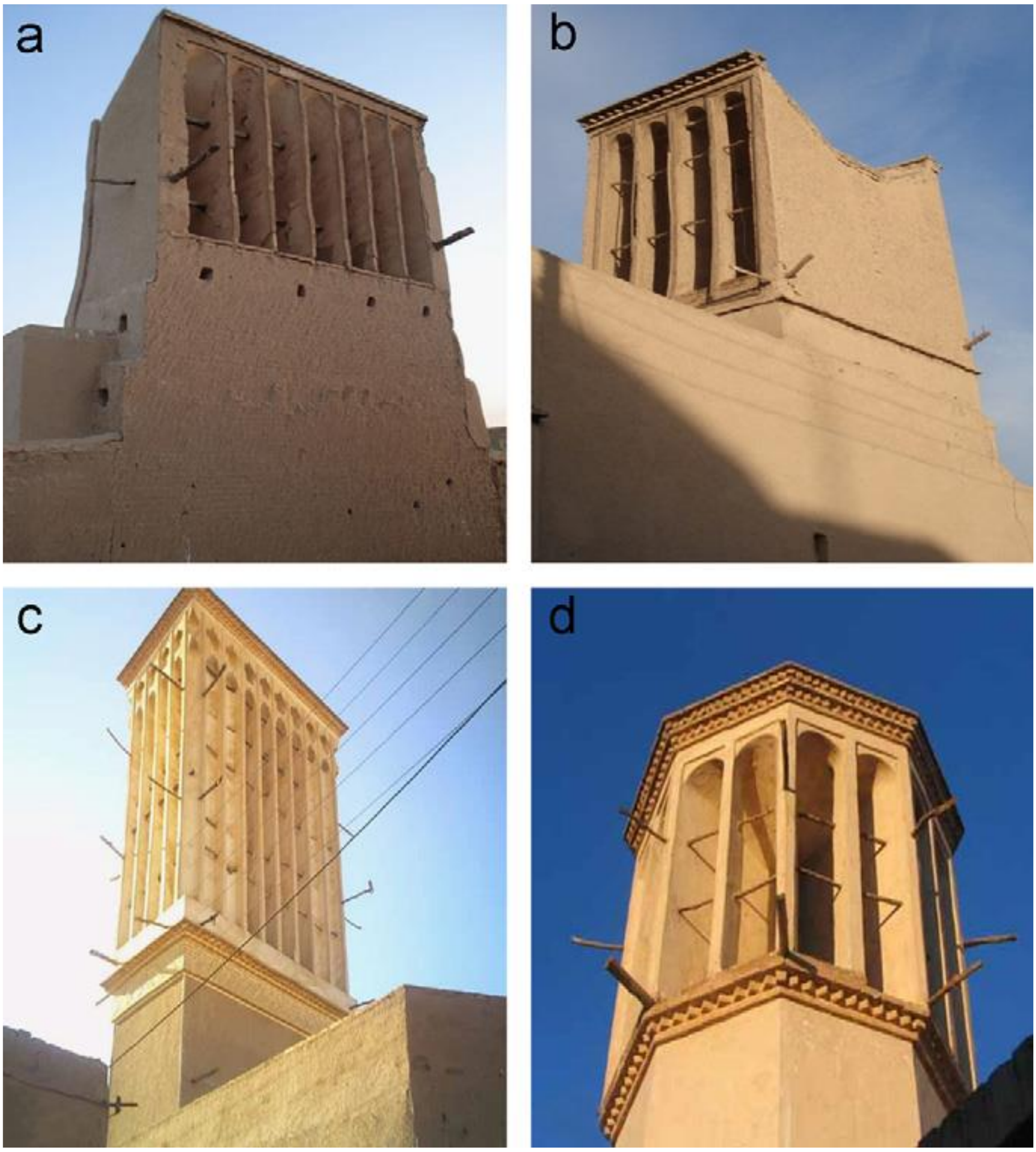


Figure 3.3.5.33: Different wind tower relevant to the number of openings, one-sided (a), two-sided(b), four sided(c) and octahedral (d) Source:(H. Montazeri & Azizian, 2008)

3.4 Conclusion

The strategies that exist for the exploitation and enhancement of natural ventilation are various. They all use the two aforementioned phenomena but in a different way and percentage. Cross-ventilation, for example, benefits more with wind driven than with buoyancy driven. As for the single sided ventilation, both effects can be applied, but again they are not as strong as in other strategies. Night ventilation also takes advantage of both phenomena and shows equally important results. The solar chimney is designed to take advantage of the possibility of buoyancy driven. Hence, it appears to have better results in this phenomenon. Finally, the wind catcher, depending on its design, can enhance both phenomena, with significant results in both cases. However, these strategies are influenced by various factors as it is mentioned in previous paragraphs. Therefore, it is important to analyze the most important ones because when designing the above strategies they can provide them either with positive results or with negative results. The next chapter will analyze the parameters that affect these strategies, such as climate conditions, surrounding buildings etc.

4 Building typology and natural ventilation strategies

In addition to the natural cooling technique that will be used in the building to reduce cooling loads, there are other factors that contribute along with them. These factors have to do with the typology of the building. The typology of the building is very essential for the engineers to understand the vulnerabilities, the behavior in the various climate changes, the availability of materials, and how to deal with them (Lang et al., 2018). Factors that affect the characteristics of the building may be the thermal mass of the materials, the orientation of the building, the ratio of walls and openings, the local environment, the climatic conditions, and other factors that are not the subject of this dissertation. The following paragraphs will described the factors mentioned and how they affect positively or negatively the need for cooling the building.

4.1 Thermal mass

Thermal mass is one of the factors that affect both thermal comfort and the performance of natural ventilation. Thermal mass can contribute significantly to the reduction of cooling loads and indoor air temperature fluctuations in buildings. Besides, the thermal mass of the material could have a favorable effect on the indoor conditions during the cooling period (Balaras, 1996). Thermal storage can be a strategy for optimizing and rationalizing natural ventilation techniques, especially in cases where energy supply and demand have some discrepancies (F. Calcerano et al., 2017).

Someone may wonder how thermal mass and natural ventilation have a relation to achieving thermal comfort conditions. This would be a logical question but in reality, as it will be described in the following lines, they have a direct connection. First of all, thermal mass or thermal storage of a building or material determines its ability to store heat energy (Reilly & Kinnane, 2017). Moreover, it can be used as an intermediate storage medium for heat sink during a day (Asfour, 2015). To this extent, many studies distinguish the several types of energy storage (C. Calcerano, 2014; F. Calcerano et al., 2017; Karlsson, 2012; Reilly & Kinnane, 2017):

- Sensible heat storage, depending on the thermal capacitance of structural materials
- Latent heat storage, phase change material are classified in this energy storage
- Chemical storage, a substance inside the material which occurs after years of use

The most used heat storage in building is sensible heat storage, since each material, depending on the thermophysical properties and temperature differences between outdoor and indoor environment, absorbs and conserves heat.

Apart from materials' thermophysical properties, the location of buildings' thermal mass plays an important role and can be divided into two basic types (J. Zhou et al., 2008):

- External thermal mass, exposed directly both to the outdoor air and indoor air (external walls, roofs etc.).
- Internal thermal mass, exposed only to the internal space (furniture and partitions).

Another parameter that a designer should consider at the design stage of a building is the occupants who will use and live in. The way that they will utilize the ability of any building system, thermal mass also, can determine the efficiency of thermal mass (Balaras, 1996).

The combination of natural ventilation and thermal mass can provide with positive solutions on how to improve the performance of a building. The thermal mass usage can both moderate the variances of indoor air temperature and create a time lag between the incident of outdoor and indoor maximum temperature (Li & Xu, 2006; Mat Santamouris & Wouters, 2006; D. Yang & Guo, 2016; L. Yang & Li, 2008). The required time of transfer of a heat wave from the outer surface of a wall to its inner surface, is called time lag. At night time natural ventilation accelerates the convective heat losses rate from the mass of the building and drives it out to the ambient, which works as a heat sink, because of lower temperatures (Balaras, 1996). Night ventilation usually decongests the internal thermal mass of the building (Li & Xu, 2006). The phenomenon that takes place for the natural ventilation in large percentages is stack effect, because warm air of internal space attempt to find a way to dissipate with the cool of outdoor air when there is open areas. Yam et al. (Yam et al., 2003) indicates that the buoyance driven natural ventilation and thermal mass are correlated in a nonlinear manner. In other words, both ventilation flow rate and indoor air temperature vary periodically but not simultaneously (Figure 4.1.1).

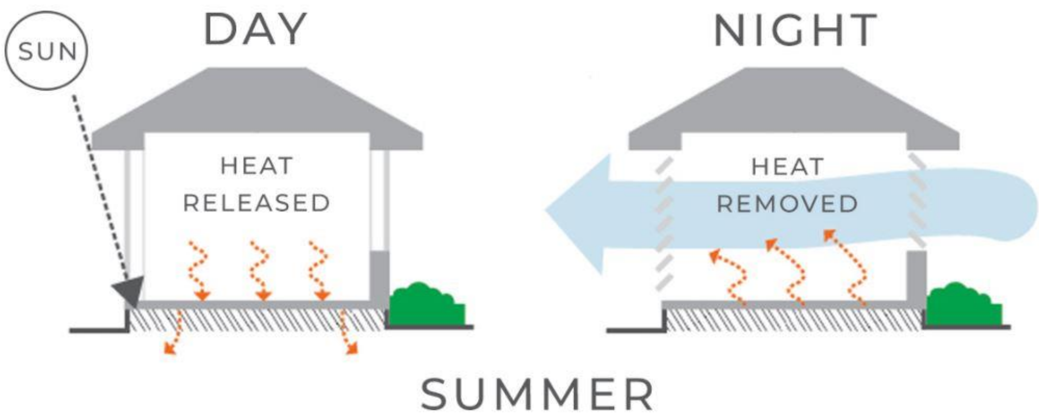


Figure 4.1.1: Thermal mass and night ventilation Source: https://acarchitects.biz/thermal-mass/

Many studies were carried and reported that a heavy construction (reinforced concrete had been used in building's skeleton) compare to a light construction (wood and brick had been used) have better results and the coupled of natural ventilation and thermal mass works more efficiently (Figure 4.1.2).(Asfour, 2015; Balaras, 1996; C. Calcerano, 2014; F. Calcerano et al., 2017; Gagliano et al., 2016a; Li & Xu, 2006; Reilly & Kinnane, 2017; Mat Santamouris & Wouters, 2006; J. Zhou et al., 2008).

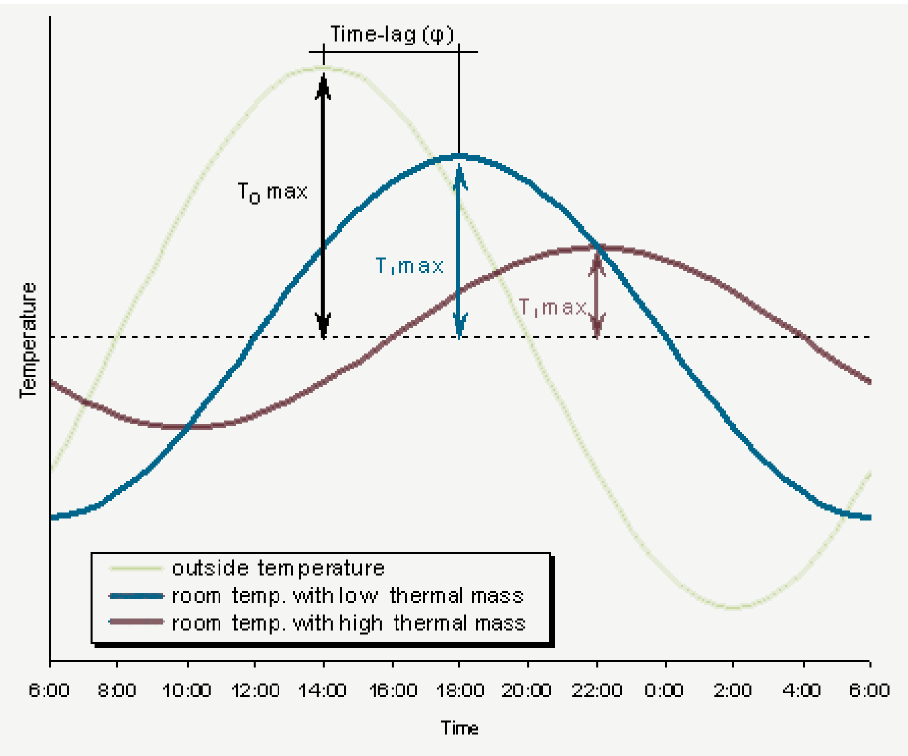


Figure 4.1.2: The difference of heavy construction (high thermal mass) and light construction (light thermal mass)
Source:https://www.daviddarling.info/encyclopedia/T/AE_thermal_mass.html

4.2 Orientation

During the design phase of a passive building, engineers have the opportunity to study, predict, and avoid possible errors. Thus, in a passive building, the use of passive systems is deemed necessary to reduce the energy consumption of the building, there is a factor that can affect all of this operation efficiency of them. This factor is the orientation of the building. The strong relationship between the orientation of the building and its energy consumption is enough to influence its operating costs. Therefore, the building should be oriented in order to reduce unwanted solar gains and maximize natural ventilation (Figure 4.2.1) (M. Al-Tamimi et al., 2011).

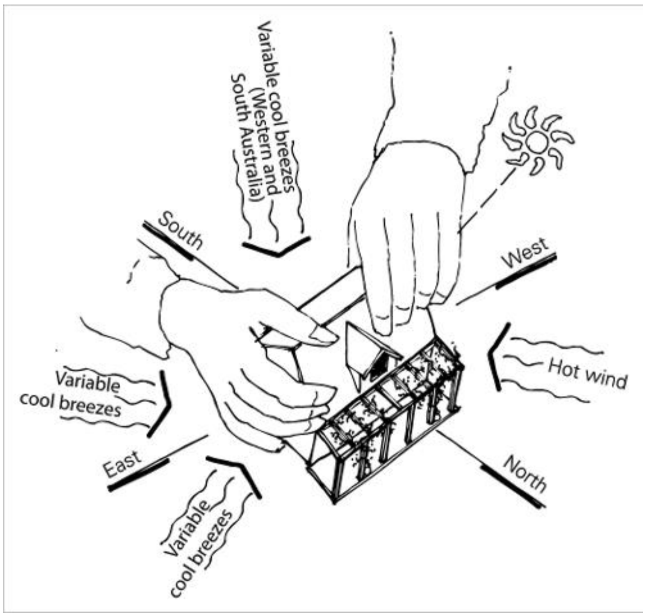


Figure 4.2.1: Orientation Selection Source: https://www.yourhome.gov.au/passive-design/orientation

Studies were carried out unanimously accept that the best orientation of the building to achieve maximum efficiency of natural ventilation is in accordance with the prevailing direction of air on an annual basis (E. Aranovitch, E. de Oliveira Fernados, 1990; Nie et al., 2015; Mat Santamouris & Wouters, 2006). According to Rodenbaum (Rosenbaum, 1999), who has done many projects about air movement, conclude that the buildings should be faced at an oblique angle to the prevailing wind is more efficient than facing it perpendicular position relative to the prevailing wind. The angle of the wind direction and the facades of the building influence natural ventilation potential and building energy consumption (AbdelRahman et al., 2017a; Haase & Amato, 2009; T. W. Wang et al., 2020; C. Zhou et al., 2014)

A survey was conducted by Sumei Liu et al (Liu et al., 2014), at the University of Tianjin, in China, focused on the combination of natural ventilation and daylighting for residential community buildings at the design stage. Simulations were made for natural ventilation relative to building space and building orientation. After finding the most effective distance between the buildings, keeping the distance between them constant, they ran various simulations changing the orientation. They found that the “building pressure difference” was affected by +13% and “unit pressure difference” as well by +27%. The conclusion of the survey was that the pressure difference rises as the angle between the building north axis decreases.

Another survey was carried out by Wei Yin, Guoqiang Zhang, Wei Yang and Xiao Wang (Yin et al., 2010), who showed that the potential of natural ventilation can be affected by the orientation. They designed a model with two openings and simulated it in four different cities in China with different climatic conditions. Two types of directions were considered, OA (orientation north and south) and OB (orientation west and east). The results indicated that the OB orientation had fewer total hours of natural ventilation than OA orientation and the volume of total ventilation was lower enough for all studied cities.

The same results were obtained in another survey conducted by Peng Nie and his team (Nie et al., 2015). A residential building model has been designed for Changsha‘s climatic conditions. They observed that if the building was designed only in relation to wind direction, the west and east orientation would be the best option. Nevertheless, the energy consumption of the building was increasing in these orientations. They did a diagram in order to find the best orientation, which would satisfy the natural ventilation and building energy consumption simultaneously. The results show that the best balance point of orientation is between the south and north.

Thus, the orientation of the building is a factor that induces the natural ventilation potential (wind drive in most cases) and even more the energy consumption of the building.

4.3 Wall window ratio

The orientation of the building is a significant factor that significantly affects the pressure differences around the building and therefore, the efficiency of natural ventilation inside it. Another factor to consider by engineers at the design stage is the ratio of windows to walls. The windows are not only a medium via them occupants come into visual contact with the outside environment, but they also offer him protection from various weather conditions. The division of the window area to the external wall area gives the result of the window to wall ratio in percentage.

Various studies have found that apart from the shape and orientation of the windows, an important factor is their size (Cho et al., 2012; Heiselberg & Sandberg, 2006; Kyritsi & Michael, 2020). The size of the openings is directly related to the discharge coefficient. The discharge coefficient is one of the characteristics of the openings that during the design stage of a building it is wise for the engineer to deal with (Heiselberg & Sandberg, 2006). A proper collaboration of the optimal opening area and natural ventilation can minimize the indoor temperature by restricting the excess solar radiation (Al-Tamimi & Fadzil, 2010; M. Al-Tamimi et al., 2011).

Abdelsalam Aldawoud conducted a survey that examines how the ventilation rate is influenced by varying the size of the window (Aldawoud, 2017). He constructed a standard office building, whose thermal characteristics of the building's envelope (external walls, floors, and roofs construction) were designed following the ASHRAE 90.1-2007 envelope requirements. Besides, the climatic conditions of Dubai, in the United Arab Emirates, were used because the simulation would run for a hot and humid climate. The various scenarios had as variable factor the change of the percentage of windows both on the windward side and the leeward side of the building. The range that he examined for then outlet and inlet area was 10% to a maximum of 50%, starting as 10% for both sides for representing benchmark. After simulating the various scenarios, he concluded that the larger the surface area of the openings on the windward side compared to the leeward side, the better the natural ventilation effect.

Another study, which is very interesting, had as an object the utilization of double skin perforated façade on buildings to optimize the energy performance of them through natural ventilation and daylight. The study took place in Japan and was conducted by Thanyalak Srisamranrungruang (Srisamranrungruang & Hiyama, 2020)and Kyosuke Hiyama (Srisamranrungruang & Hiyama, 2020). The double perforated facades has been used to optimize the energy contribution of natural ventilation and daylight. It operates like the conventional window but the difference is that the facade is full of holes **(**Figure 4.3.1**)**.

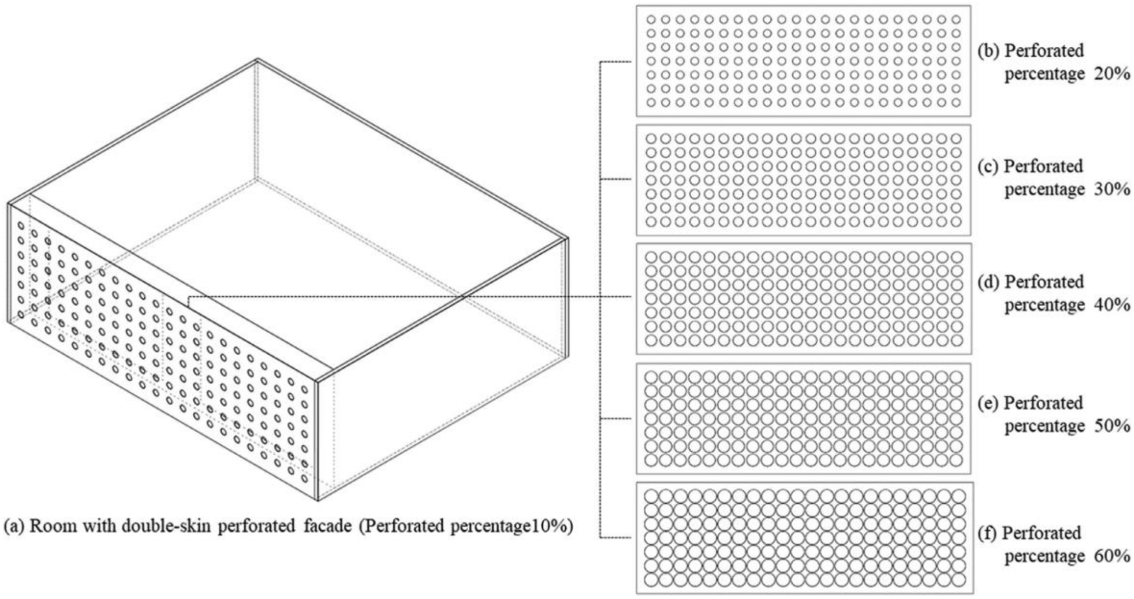


Figure 4.3.1: Perforated faced Source:(Srisamranrungruang & Hiyama, 2020)

They did many simulation by changing the perforated percentage, as the Figure 4.3.1 shows. The conclusion of the research was the percentage varies depending on the weather conditions. For instance the best option in spring was 60% and in autumn 10% and through a year is 30%.

Window wall ratio does not always contribute positively as the ratio increases. A study which were occurred in hot humid climate in, showed different results. Nedhal Ahmed M. Al-Tamimi and Sharifah Fairuz Syed Fadzild examin (Al-Tamimi & Fadzil, 2010) a typical hostel room at USM, Penang in Malaysia, which faced east and has WWR of 50%. They attempted to optimize the energy performance of the room by changing the WWR. The cases, depending on WWR, was three 1) the excisting WWR of 50%, 2) WWR 25% and 3) WWR of 00%. The results indicates that the WWR of 25% can improve the thermal comfort by applying natural ventilation.

To conclude, window wall ratio (WWR) can achieve energy savings and enhance natural ventilation application if it was designed properly. The characteristics of the openings also have their impacts (Hassan et al., 2007) and the design stage is factor that determines the future of the building.

4.4 Surroundings

Natural ventilation is a very important factor that can improve the thermal comfort of the indoor environment of a building. The air, which is abundant in the environment, is what causes these thermal changes inside the building when it comes to natural ventilation. Nevertheless, before entering the building during its course, various objects are presented, such as buildings, trees, bushes, etc. The microclimate around the buildings, which is landforms, trees and other nearby buildings, greatly affects the local wind conditions (Mat Santamouris & Wouters, 2006). These objects cause changes in air temperature, humidity, and direction. This subchapter will discuss the ways in which adjacent buildings and the surrounding vegetation affect the natural ventilation around of an understudy building.

4.4.1 Adjacent buildings

Urban environment many buildings have been built as a group or close enough to each other. The surface pressures will be strongly affected by the surroundings appearance. In addition, the surrounding built up environment can cause difficulties to obtain large enough pressure differences around of a building in order to provide it with adequate fresh conditioned air (Bauman et al., 1988). Except for the pressure differences across a building, the wind velocity and wind direction can be affected by the configurations of the surrounding buildings.

In Hong Kong, for instance, C.F. Gao and W.L. Lee (Gao & Lee, 2012) conduct a study about the influence of surrounding buildings in order to investigate the natural ventilation performance of residential building. The model that they designed, consisting of a city of 52 blocks by changing the wind's direction and velocity. The results indicates a significant speed reduction for all wind direction, a range of it -2.5% to -86.8%. Moreover, an angular spread of wind direction was increased and an anti-clockwise shifting was occurred with range of 5^o to 32^o. Therefore, the indoor ventilation level was decreased on significant level by the presence of surrounding buildings.

The distances among building blocks can change the effectiveness of natural ventilation. Francis W.H. Yik and Yu Fat Lun (Yik & Lun, 2010) proved to their study that as the intermediate distance among building blocks were widened by 25% and 50%, it can be achieved additional energy savings.

Plenty of studies have occurred and their results indicate the affection of surrounding buildings both in the efficiency of natural ventilation and in the energy performance of the sub-designed buildings (Abd Razak et al., 2013; Jin et al., 2013; Pisello et al., 2016a; Stathopoulos & Storms, 1986; van Hooff & Blocken, 2010). The conclusion of these researches was that the denser surrounding buildings are the less natural ventilation can occur.

4.4.2 Vegetation

The surrounding buildings that may exist are one of the factors that affect the natural ventilation of a building. The other factor is the presence of vegetation. The thermal efficiency of a building can be significantly affected by the presence of vegetation at the microclimatic level. Vegetation generally changes temperature, humidity, and radiation rate to a significant level (McPherson et al., 1988). When the ambient temperature increases human body through perspiration mechanism reduces excess heat when air flows through the skin via evaporation, take the advantage of latent heat (Mat Santamouris & Wouters, 2006). The same applies when the air flows around the plants' leaves.

Web bulb temperature is commonly accepted that reaches lower temperatures than dry bulb temperature. Thus, trees and other vegetation though evapotranspiration influence daily temperature fluctuations by adding moisture in the air via leaves. Y.J. Huang et al (Taha et al., 1988) claims that an increase of 25% vegetation can lead to a reduction of annual cooling energy use of 40% of an average house in Sacramento, and 25% in Phoenix and Lake Charles. Most of this percentage is generated by evaporation, which reduces the ambient temperature, and through natural ventilation, this reduced temperature is introduced into the buildings and thus reducing its cooling demands.

Dan m. Kurn, Sarah E. Bretz, Benson Huang and Hashem Akbari estimate that a vegetates areas can contribute to the reduction of cooling loads in residential buildings (Kurn et al., 1994).

It is worth noting that the literature review shows limited evidence for the study of this topic. The presence of plants around a building and in which point they can be dense so that the desired airspeed is not significantly affected. Also the increased presence of vegetation can cause thermal discomfort to the indoor environment of a building due to high humidity levels.

4.5 Climate

Various pressure differences and temperatures, which take place in the environment, occur the air motion and both are strongly related to climatic conditions, Climate varies greatly from continent to continent even from region to region in the same country. The parameters that are affected by climate changes are ambient temperature, humidity, precipitation, wind, atmospheric pressure and other meteorological parameters. The worldwide most used classification for climate is Köppen-Geinger classification. It describes the prevailing climate of a region in relation to temperature and precipitation (Kottek et al., 2006)(Figure 4.5.1).

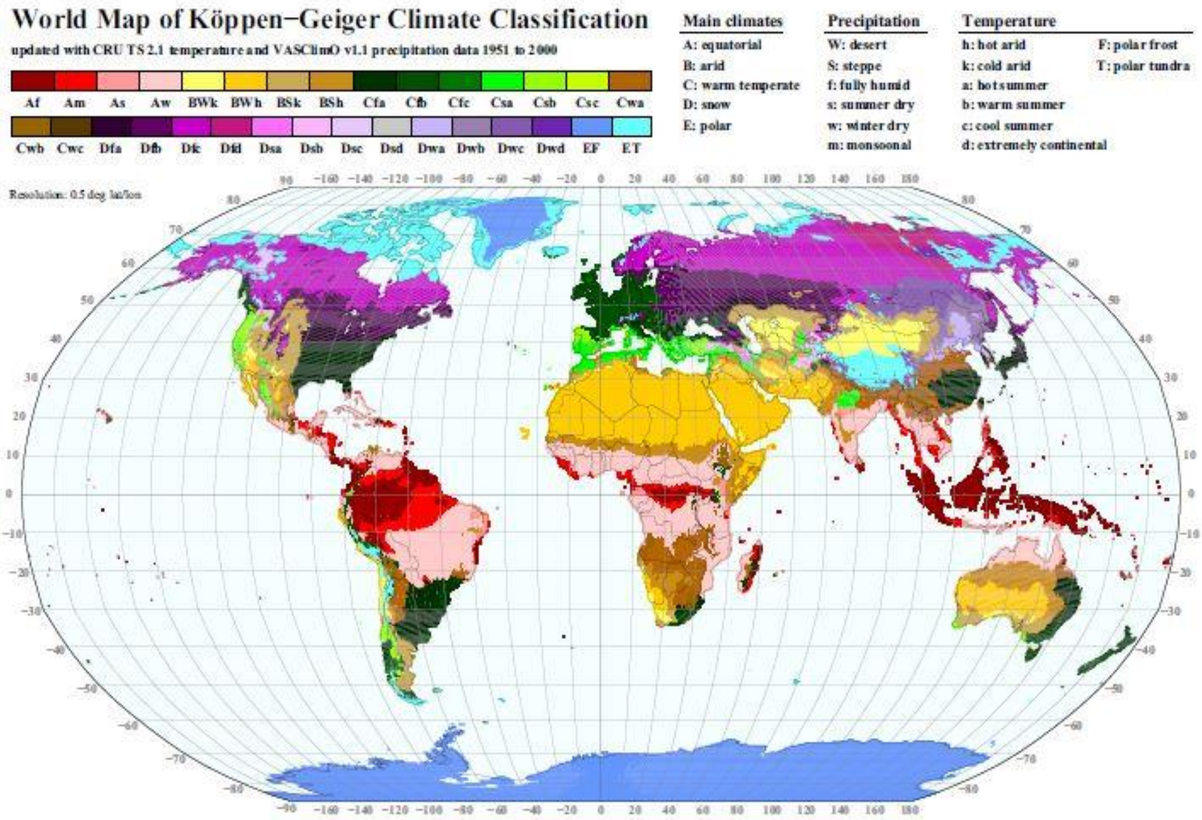


Figure 4.5.1: Köppen-Geinger Climate Classification Source:(Kottek et al., 2006)

Climatic conditions in most cases determine the natural ventilation potential in a region and its performance. Yujiao Chen, Zheming Tong and Ali Malkawi (Chen et al., 2017) conduct a study in order to investigate the possibilities of natural ventilation that would occur in various climatic conditions. They analyzed climate data at 1854 locations from six continents and designed an office building of a gross floor area of 4982m^2, which was a reference building of the U.S. Department of Energy. The results showed a significant impact on the energy performance of the building relative to thermal comfort and

NV (natural ventilation) hours. Many regions appear to have great potential for utilizing natural ventilation (Figure 4.5.2).

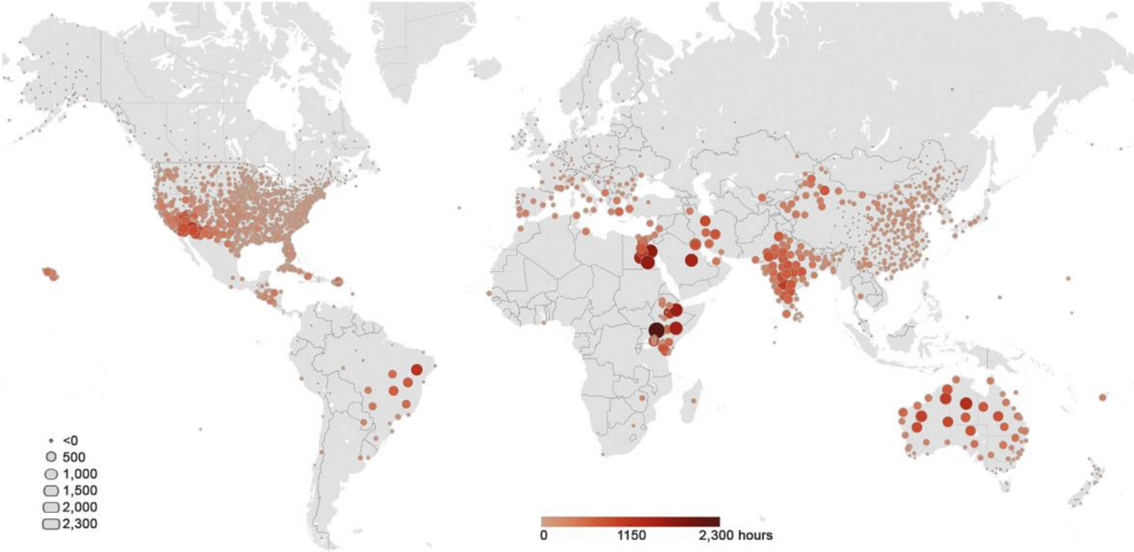


Figure 4.5.2: NV hours gained obtained using an adaptive thermal comfort model. Source :(Chen et al., 2017)

The next figure from this research is interesting, because indicates the energy savings of the world's 60 largest cities were achieved via natural ventilation uses (Figure 4.5.3).

City	NV hour	Non-NV hour (hot and humid)	NV%	ES%
Tokyo	2633	2131	55.3%	27.5%
Delhi	3331	4572	42.1%	13.3%
Manila	7	8753	0.1%	0.0%
Seoul	2423	1967	55.2%	26.5%
Karachi	2701	5799	31.8%	7.6%
Shanghai	2302	3325	40.9%	20.8%
Mumbai	1373	7387	15.7%	1.9%
New York	2966	1573	65.3%	23.0%
Sao Paulo	5164	3215	61.6%	27.2%
Beijing	2651	1907	58.2%	21.7%
Mexico City	7161	104	98.6%	32.3%
Guangzhou	2434	5358	31.2%	15.1%
Dhaka	2240	6428	25.8%	4.6%
Osaka	2969	2381	55.5%	24.2%
Moscow	2378	193	92.5%	31.7%
Cairo	4886	3187	60.5%	26.1%
Bangkok	606	8154	6.9%	0.8%
Los Angeles	7197	526	93.2%	49.8%
Buenos Aires	4514	1690	72.8%	39.2%
Kolkata	1785	6928	20.5%	4.5%
Tehran	4253	1240	77.4%	24.0%
Istanbul	3577	1436	71.4%	28.5%
Tianjin	2643	2076	56.0%	19.3%
Rio de Janeiro	1518	7241	17.3%	3.6%
Lima	5974	2784	68.2%	38.9%
Chengdu	2660	3153	45.8%	24.2%
Paris	3451	161	95.5%	45.4%
Bangalore	3100	5660	35.4%	7.3%
London	2885	57	98.1%	45.9%
Chennai	120	8640	1.4%	0.0%

City	NV hour	Non-NV hour (hot and humid)	NV%	ES%
Nagoya	3031	2241	57.5%	24.9%
Hyderabad	2471	6283	28.2%	6.0%
Chicago	2808	1368	67.2%	20.7%
Johannesburg	6105	219	96.5%	30.3%
Shenyang	2182	1682	56.5%	20.1%
Wuhan	2122	3433	38.2%	16.1%
Kuala Lumpur	0	8760	0.0%	0.0%
Hong Kong	2840	5671	33.4%	16.8%
Boston	2745	1136	70.7%	27.3%
Zhengzhou	2553	2404	51.5%	17.5%
Hangzhou	2193	3428	39.0%	17.8%
Dusseldorf	3294	136	96.0%	46.5%
Toronto	2489	702	78.0%	26.3%
Dallas	2938	3174	48.1%	16.9%
San Francisco	5337	57	98.9%	49.2%
Nanjing	2246	3015	42.7%	19.8%
Madrid	4074	703	85.3%	36.1%
Santiago	4297	565	88.4%	39.2%
Houston	2927	4595	38.9%	16.9%
Miami	1906	6675	22.2%	6.4%
Riyadh	4916	3110	61.3%	24.7%
Singapore	0	8760	0.0%	0.0%
Xi'an	2735	2145	56.0%	21.7%
Philadelphia	2883	1775	61.9%	25.4%
Nairobi	8435	179	97.9%	43.5%
Milan	3221	934	77.5%	28.9%
Atlanta	2674	2798	48.9%	21.3%
St. Petersburg	2164	82	96.3%	37.2%
Washington	2601	2169	54.5%	22.5%
Barcelona	3803	1776	68.2%	38.1%

Figure 4.5.3: NV hour and ES (Energy-saving) obtained in respective of 60 world's largest cities Source(Chen et al., 2017)

It seems regions with hot and humid climate have weak or no natural ventilation potential.

Many studies were carried out to investigate the impact of climate in different regions. Hot and dry climate temperature variations affect the indoor environment of a dwelling. Hamdani et al (Hamdani et al., 2017) simulated a building in Algeria, where in this region prevails hot and dry climate. The temperature appears with large fluctuation during summer and exploiting night ventilation, energy savings were achieved for the simulated building. The same results were obtained in a study that had as an object an apartment block of a 12-story high building with four units on each floor (Rajasekar et al., 2014). Researchers find a significant variation diurnally and seasonally were occurred through year and night ventilation aided to achieve thermal comfort.

Not only in hot and dry climates buildings can reduce their energy consumption in conjunction with natural ventilation. Studies were carried out in other climatic conditions. Also, in buildings that have been built in a hot and humid climate, occupants can benefit from natural ventilation. A study were conducted in Naha, Japan, in which the climate is hot and humid, showed that natural ventilation can enhance to reduce the cooling loads and energy consumption by achieving a thermal comfort environment in a porous residential building (Hirano et al., 2006). In China, another assessment was carried out in five cities in the humid subtropical climate zone. In this study, researchers collected enough questionnaire responses and found that occupants were more tolerant in naturally ventilated buildings, even though a comparison of various methods of assessing that they used reveals the opposite statement (W. Yang & Zhang, 2008).

In Mexico, where warm climate dominant, Ivan Oropeza_Perez and Poul Alberg Østergaard (Oropeza-Perez & Ostergaard, 2014) surveyed 27 common cases of dwellings. They conclude that in a hot and dry climate is more likely to benefit from natural ventilation in a dwelling than in a humid climate. Many other studies were occurred in a different climate like cold climate and show that natural ventilation is not available in all cases or if it were, the results would be slightly better than mechanical ventilation (Calautit et al., 2016, 2020; Simonson, 2005; Z. Wang et al., 2010).

Climate change in the future maybe or surely will affect the natural ventilation effectiveness and thus the energy performance of a dwelling. It is more rational, architectures and engineers to design buildings relative to the climate change for the lifetime of the understudy building. The study of Victor Perez Andreu et al, who includes many other studies, forecasted the impact that a residential building would have concerning climate change (Pérez-Andreu et al., 2018).

4.6 Overview of Greece

Factors affecting the performance of passive ventilation systems were presented in the previous paragraph. This section will describe the above factors according to the current situation in Greece, but also their best. The factors will be commented in order as described previously.

4.6.1 Thermal mass

As mentioned above, the heat capacity of the materials aids in the smooth fluctuation of temperature variations between the indoor space and the outdoor environment. Thus, the higher the material's thermal mass is, the greater the time lag. Materials that are considered to have the ability to store high amounts of thermal energy are cement, bricks, and tiles (Balaras, 1996; Shafigh et al., 2018). Therefore, countries that uses as main materials the aforementioned for the construction of buildings, they are characterized by high thermal mass. In Greece, buildings are constructed mainly with these materials. More precisely, reinforced concrete is used for the construction of the building frame (beams, columns, slabs, etc.). In addition, the filling masonries are almost all constructed of bricks and the roofs are covered either with tiles (inclined roof) or terraces with reinforced concrete. Therefore, the buildings in Greece are characterized by high herma mass structures meaning that they have a positive probability for the application of natural ventilation (Theodoridou et al., 2011).

4.6.2 Wall window ratio

The window to wall ratio determines the efficiency of natural ventilation. The factors that are mainly affected by this ratio are the wind velocity and the route that the indoor air will perform. Thus, the WWR is one of the factors that affects natural ventilation performance.

In Mediterranean climates, in countries that are located above the equator, such as Greece, buildings tend to have a large percentage of openings on the south side (Tzoufis Dimitrios Kosmas, Christodoulou Nikos. (n.d.)., Online et al., 2018) while on the north side of the building the frames occupy the next largest percentage. As far as both the west and east side are concerned, openings occupy the lowest percentage (Online et al., 2018). However, the literature review so far has not shown strong results with limited case studies on the WWR for either Greek residential buildings or residential buildings in Mediterranean climate zones in general. In researches carried out for the optimal design of the residential building envelope in a Mediterranean climate, one of them referred in Athens (Ascione et al., 2016). The results showed that a WWR of 30 to 50% presents the best results (Ascione et al., 2016; Elnagar & Köhler, 2020). This ratio corresponds to the entire building envelope. On the contrary, many researches refer to office buildings in the Mediterranean climate and Greece (Chiesa et al., 2019; Fernandez-Antolin et al., 2019; Goia, 2016; Leonidaki et al., 2014). All of them agreed on a WWR of 25-40% that provide optimal results. The largest percentage is presented in the south orientation that the percentage can be outside the limits of 40%. Based on the above, it could be predicted the range that WWR can fluctuate for the climate of Greece. This ratio could range 30-40% for residential buildings in Greece for the entire surface of the building with more emphasis on the south and north side.

4.6.3 Surroundings

In the previous paragraph was described the influence of surrounding buildings and vegetation have on natural ventilation performance. The results derive from different surveys shows (Abd Razak et al., 2013; Jin et al., 2013; Pisello et al., 2016b; Stathopoulos & Storms, 1986; van Hooff & Blocken, 2010) that the denser an area is from buildings the less natural ventilation potential. On the other hand, the presence of surrounding vegetation can be beneficial (Taha et al., 1988).

Most population in Greece lives or moves to urban areas. The result of that trend is that the urban areas are becoming denser in buildings. Moreover, insufficient urban design in Greece creates problems such as inadequate wind and higher temperatures (Urban Heat Island). The high proportion of buildings and the low proportion of vegetation in cities do not act positively for natural ventilation. Thus, in urban areas are recorded high temperatures and low wind velocity. (Giannaros & Melas, 2012; Nikos Papamanolis, 2015). In contrast, rural areas are sparsely populated in Greece, which acts positively for wind velocity and more comfortable temperatures. Hence, the probability of natural ventilation is more feasible in these areas. (Giannaros & Melas, 2012; Nikos Papamanolis, 2015). Thus, passive cooling design would be more feasible in rural areas than urban areas, without being unattainable. This mean that the urban design in Greece should be careful design and consider to have enough space between the buildings, to ensure the appropriate distances from the opposite buildings and to plant more vegetation in the cities. All these changes can improve the natural ventilation performance. The gap between the buildings make wind to move more freely with high velocities and vegetation reduces the ambient temperature.

4.6.4 Orientation

A proper orientation determines many beneficial factors for building and passive cooling strategies. In south Mediterranean countries, which their latitude is about 40°, as an optional orientation for both winter and summer period is south. It has been calculated that buildings with their main facade oriented at the south achieved a lower annual energy consumption in both heating and cooling (Online et al., 2018). According to Chronopoulos S., Nastos P., and Kampanis N. survey, the prevailing wind in Greece is north and northeast direction (Chronopoulou et. al. (2010). That means that the building is preferable to be orientated in these directions in order to take the full advantage of natural ventilation. A tolerance of ±30° from South-North Axe is acceptable (Online et al., 2018). Thus, an orientation with ±30° can be beneficial for both solar radiation and natural ventilation in Greece.

4.6.5 Climate

Greece is a country, where is situated at the southern east borders of the European continent. The climate in Greece is a typical Mediterranean climate. It is divided into two seasons, the mild and rainy season and the warm and dry season. According to the Köppen Climate classification, Greece has a mild temperate climate with dry summer or in some regions fully humid and hot summer (Csa or Cfa) (**Figure 4.6.1**). The cold season for Greece starts in October and finishes in March. As the warm season is between April and September. Most days of the year have sunshine, but the winter period has the most rainfalls. In January and February, the lowest temperatures are presented. The range of low temperature in coastal regions is between 5°C and 10°C, in the mainland has 0-5°C and on the mountains can reach up to -25°C. Generally, northern Greece has a lower temperature than the rest country. In the summer period, the maximum temperature fluctuates from 29°C to 35°C. As it was mentioned, the prevail annual wind direction is north and northeast. Finally, the high levels of humidity derive because of the Mediterranean Sea (Hellenic National Meteorological Service, 2011)(Online et al., 2018; N. Papamanolis, 2000, 2005; Nikos Papamanolis, 2015).

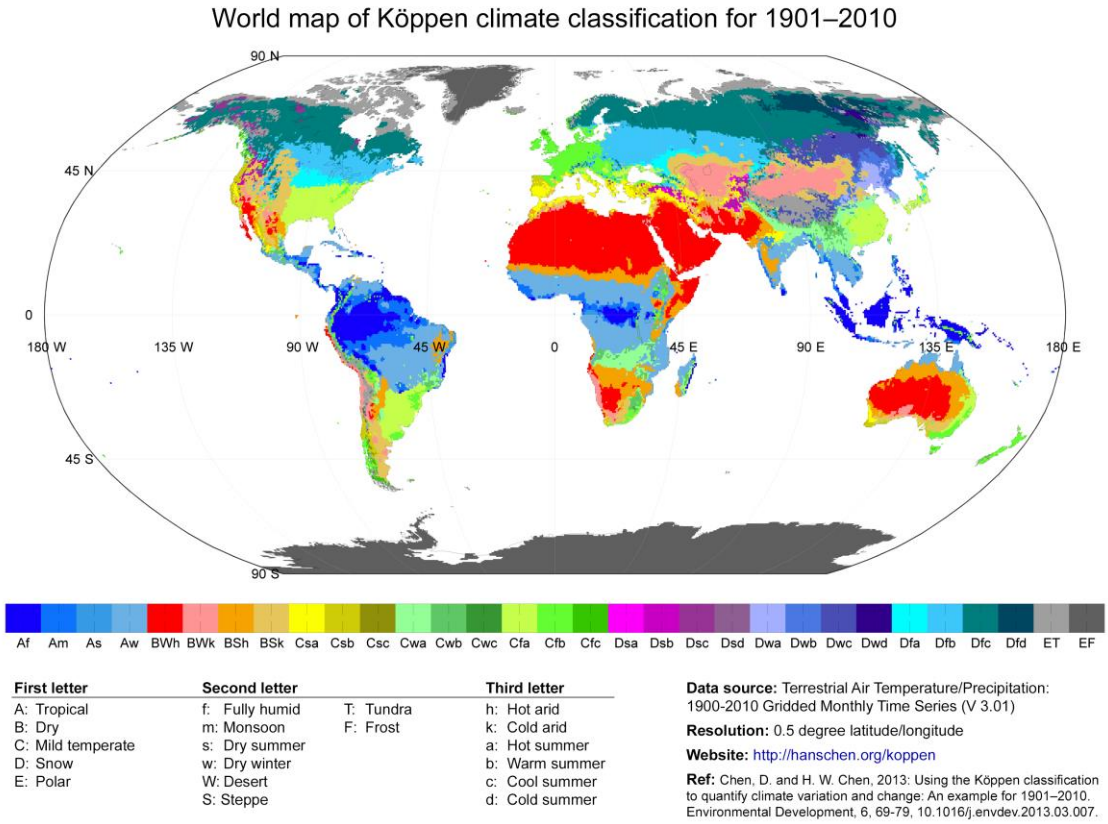


Figure 4.6.1: Climate of Greece in Köppen Climate Classification
Source: http://hanschen.org/koppen

4.7 Conclusion

In this chapter, factors that significantly affect the performance of different passive systems were presented. The thermal storage capacity of the element significantly helps to avoid overheating the interior space and also the efficiency of natural ventilation. A heavy structure building has a better behavior in the fluctuation of the internal temperature and maintains lower temperatures during the day. In combination with ventilation, especially night ventilation, a comfortable indoor environment is achieved. On the other hand, the orientation aids to maximize the possibility of exploiting the outside air to enter the inside of the shell. Orientation contributes to the better performance of passive systems such as cross-ventilation or grip wind. The window wall ratio of the building determines the amount of solar radiation that will penetrate, but also the speed and the amount of air that will introduce into space. The surrounding buildings, as well as the surrounding vegetation, in most cases, prevent the passage of wind. The reduction caused is usually the change in air direction and velocity. The vegetation, in comparison with the surrounding buildings, also helps to reduce the temperature of the introduced air, which has the effect of enhancing the efficiency of natural ventilation. Finally, climate and general weather conditions are one of the most important factors that affect the operation of passive systems. Different climatic conditions have different impact on the passive systems performance.

Natural ventilation is not an easy task, as evidenced by the analysis done above. The analysis was based on questions about how natural ventilation occurs, what the most common systems are, how they work and what factors affect them. Thus, after being answered in detail, a designer is now able to understand what he should study. The simulation that will be called to do also has its requirements. The designer is faced with many parameters and a variety of programs that he should choose for his study. The choice of a program is influenced by the different possibilities and details in the methodology it provides. Therefore, the next chapter will describe the two types of programs that exist to simulate both the ventilation and the energy efficiency of the building.

5 Methodologies

Many passive cooling techniques and strategies can be applied to a building. Moreover, the typology of the building, the surrounding objects, and climatic conditions have impact on the overall energy performance of the building and natural ventilation efficiency. The designer should consider in what degree the selected design influence natural ventilation and in what the introduction percentage is for the wind. Thus, the selection of the proper software and methodology are those which determines the final results of the study.

The use of the correct methodology and approach of a study can ensure greater accuracy and avoid significant errors in the results. Thus, the architect and engineer during the design stage of a building are called to study the various effects and the different results that the chosen approach can bring. That is why at an early stage the right use and the proper application of the methodology are necessary.

Several programs are widely used and each of them uses either the same methodologies or different approaches to compute a simulation. Some of them can be coupled with other software more analytical to provide better and more realistic results. The methods, which are mostly used, will be analyzed in this chapter relative to natural ventilation simulation. Moreover, it will be focused on specific energy simulation and airflow simulation software. Energy plus is one of the most used energy simulation software and Computational Fluid Dynamics (CFD) simulations. It will be presented their capabilities, their differences, and how one can complement the other to achieve more realistic results.

Many programs can calculate a multizone airflow and energy consumption of a building. But most of them are paid to have access on them. Some of them AIOLOS (Cardinale et al., 2003), COMIS (Conjuction of Multizone Infiltration Specialist), BREEZE, CONTAM, TRNFLOW, etc are airflow programs, which are focused on the calculations of the airflow rates in multizone buildings. As for the energy calculations of a building, the following software are widely used, such as DOE-2(Birdsall et al., 1990), TRNSYS (Osso et al., 2015; Rinaldi et al., 2017; Z. Tan & Deng, 2017; TRANSSOLAR Energietechnik, 2017), ESP-R (Strachan et al., 2008; Yao et al., 2005), DesignBuilder (Gagliano et al., 2016a; Nie et al., 2015; Pesic et al., 2018; Raji et al., 2020), EnergyPlus(Crawley et al., 2001), etc.. Energy Plus is an open source software and can provide enough and reliable results for the energy performance of a building. It can compute an airflow rate in multizone buildings, but, as will be discussed below, the results are not valid enough to aid for a decision depending on the method the user inputs. It needs to be coupled with a CFD software.

Computational fluid dynamics (CFD) software is a simulation tool providing the engineer with insights in order to optimize his design, prevent any errors, and make it more comprehensive to find the reason and solution for a problem. These types of software can predict detailed wind environments (pressure coefficient, wind direction, wind turbulence, wind velocity) around buildings. It has been used extensively in the research of forecasting and calculating natural ventilation. Also, predicts the surrounding objects' impacts on the natural ventilation potential and it is characterized as an effective tool for natural ventilation simulations. Some CFD software are FLUENT, ANSYS, etc., most of them are not open sources.

5.1 EnergyPlus

Energy Plus was developed since 1996, by a US federal agency, which is a building energy simulation tool combination of DOE-2 and BLAST, two software used for the same reason but with fewer capabilities (Crawley et al., 2001). The Energy plus calculate the energy demand of a building in heating and cooling loads by using multiple systems and energy sources (US Department of Energy, 2010). According to the data that the user will enter in the program, such as design and characteristics of the building envelope, lighting, ventilation, HVAC systems use, calculates the heating and cooling loads, lighting, ventilation, other energy flows and water use that a building requires to maintain comfortable conditions. Therefore, the Energy Plus is used for energy simulation(Lee & Strand, 2009; Oropeza-Perez & Østergaard, 2014; Z. Zhai et al., 2011).

5.2 Computational fluid dynamics (CFD) software

The idea of Computational Fluid Dynamics (CFD) initiated in the earlies of 70s and was established by the CFD group of Imperial College (Khalil, 2012). Since then more users and researchers contributes to the changes and improvements of the software in order to provide to the engineers the best results. The main functions of the CFD software are to compute with more detail insights on the heat transfer and airflow. It uses in most cases Naiver Stokes equations and in few others the Lattice Boltzmann equation to forecast fluid reactions. Thus, CFD software is used to compute the airflow and convective heat transfer (Allocca et al., 2003; Hosain & Fdhila, 2015; Hughes & Ghani, 2010; Khalil, 2012; Hamid Montazeri, 2011; R. Zhang et al., 2013a).

5.3 Differences between Energy Plus and CFD simulation software

Every software has been created for a different purpose and provides the user with limited capabilities. CFD simulation and EnergyPlus (belongs to the category of Building Energy Simulation (BES) or Energy Simulation (ES)). These software are programs with amazing features and useful capabilities offering time and money savings. However, the programs although can be used for the same purpose, they provide the user with different information even for the same understudying buildings.

The difference of the results occur due to various parameters that are considered and calculates. The first difference, which has already been mentions, is that Energy Plus provides detailed results relative to the energy performance of a building and the HVAC system used. As for CFD software computes distributions of the flow governing equation of velocity, temperature and contaminates distributions, which take place in boundary spatial configurations (Z. Zhai & Chen, 2003; Z. J. Zhai & Chen, 2005). Another difference, EnergyPlus to estimate the convective heat transfer uses empirical formulas in a well-mixed room air and enclosure indoor space (Z. Zhai & Chen, 2003; R. Zhang et al., 2013b). The CFD simulation can predict more accurate and more realistic convective surface heat transfer coefficient (Pappas & Zhai, 145 C.E.; Z. J. Zhai & Chen, 2006). Another difference, EnergyPlus takes into account a uniform temperature distribution in the indoor temperature, in contrast to CFD simulation computes the temperature stratification of interior space(Z. Zhai & Chen, 2003). A last difference, Energy plus takes boundary conditions from a weather data derived from the closest local weather station and does not account the influence of surrounding buildings, only for shading, compare to the CFD simulation, which provide more specific microclimate parameters and accounts the surroundings obstacles (Dorer et al., 2013; Shen & Wang, 2020; Yi & Malkawi, 2011) (Figure 5.3.1).

Some typical functions of ES and CFD programs for building performance studies

	ES	CFD
Weather and solar impact	Yes	No
Enclosure thermal behaviors	Yes	No
HVAC system capacity	Yes	No
Energy consumption	Yes	No
Thermal comfort (air temperature, air velocity, air humidity, and airflow turbulence)	No	Yes
Indoor air quality (contaminant concentrations)	No	Yes
Air distribution	No	Yes

Figure 5.3.1: Differences of EnergyPlus and CFD software Source:(Z. J. Zhai & Chen, 2005)

Apparently, the various studies that have been done to research the various possibilities offered by these programs could be concluded that their unilateral use can lead to overestimated results that usually lead to hasty decisions. Today, many types of research and studies are done in combination with this two software that they offer reliable results. Simulations made compared to real measurements showed that their combination brings results that are more realistic. In the next Table 5.3.1 and Table 5.3.2 are presented some of these surveys that are carried out and indicates realistic results after the combination of Energy Plus and CFD simulation programs.

Source	Studied	Results or conclusions
(Malkawi et al., 2016)	A comparison of an energy simulation. In this study, a comparison is made between the Energy Plus and CFD programs with the possibilities offered by each. This comparison is made by simulating an existing three-storey building in Cambridge, Massachusetts. More precisely, the energy efficiency of this building is studied using only the Energy Plus and then with the combination of the Energy Plus and the CFD simulation.	After applying both the scenarios and adjusting some parameters, the researchers came to the following conclusions. In the case of the buoyancy-driven mixed ventilation case, there were significant differences. Energy plus cannot simulate properly and produce realistic results for large spaces, such as atrium. Also in the case of wind-driven natural ventilation wind, the EnergyPlus provided higher results than those of the CFD simulation. This is because EnergyPlus do not consider the surrounding buildings. Thus, the CPD simulation presents results that are more realistic. Therefore, the researchers conclude that the combination of these two programs provides more accurate and comprehensive results when it comes to large spaces and surrounding buildings should be considered.
(Shan et al., 2020)	A large office was used as a simulation model, which was located in Hong Kong. The investigation of this model was occurred by applying a co-simulation of EnergyPlus and CFD software. The EnergyPlus was used to calculate the surface temperature and supply airflow rates, after the introduction of weather data, features of the office elements, internal heat gains, and mechanical ventilation system. After setting boundary conditions, CFD simulation calculated and exported insights of the stratification of the indoor thermal environment and airflow patterns. Also, CFD simulation predicted the PMV values relative to occupants' thermal comfort. After the CFD's results were resulted inserted again into EnergyPlus to perform the energy performance of the HVAC system.	After simulating different scenarios relative to various temperature setpoint, the results were the following. EnergyPlus could "feed" CFD simulation with reliable uniform interior surface temperature and air supply rate. A comparison of experimental measurement, co-simulation of EnergyPlus and CFD simulation, and CFD simulation alone indicates that co-simulation can predict more precise results to experimental measurement than CFD simulation alone. Moreover, in occupied spaces, the division of four different subzones with individual temperature setpoint presented better behavior than the single temperature setpoint of the solid area, in order to be achieved a uniform thermal environment. EnergyPlus model could overestimate the supply conditions because it assumes that the return air temperature has the same values as the temperature setpoint. In contrast, to CFD simulation which separates these values. The last result indicates that the air exchange rate between zones showed energy savings in cooling energy in the EnergyPlus.

Table 5.3.1: Co-simulation of EnergyPlus and CFD simulation studies

Source	Studied	Results or conclusions
(Shen & Wang, 2020)	Energy building performance is conducted in this survey relative to the neighborhood form and the envelope features with various U-Value in compliance with ASHRAE limitations. The weather data was entered according to the selected location, which was Chicago. The neighborhood consisted of an office, residential building, supermarket, school, and restaurants. All simulations were occurred by coupling CFD simulation (CHTC acquisition) and Energy Plus (energy calculations). Another object of this study was the comparison of the ASHRAE 2004 and 2016.	The results indicated that the convective heat transfer coefficient (CHTC) was influenced greatly by the height of the surrounding buildings and the form of the neighborhood due to the wind variations. High-rise buildings yielded larger values for CTHC than low-rise buildings. Another factor was that the mean wall external temperature was affected by the appearance of surrounding buildings. As ASHRAE 2016 provided better building energy performance than ASHRAE 2004, because of the improvement of the envelope thermal performance.
(Webb, 2013)	A review of under floor air distribution (UFAD) has occurred and why these types of systems are gaining more and more ground in clients' references. The system was implemented in a multi-story office building that would be constructed in Melbourne, Australia. The use of combinations of EnergyPlus (BES) and CFD simulation programs aided to provide the researchers with the possibility to design and evaluate the use of the UFAD system to achieve thermal comfort in PMV Values in summer period.	The results showed that the coupled of EnergyPlus and CFD simulation predicted positive reaction of the occupants. Specifically, the PMV value was under -1, which means that in summer period would feel cool. A prediction of air flow rate was calculated to assess the capability of the system, which was at the acceptable levels
(Performance et al., 2018b)	In this study, it was examined the effectiveness by using a ceiling fan integrated in a building model. The assessment was done according to the thermal comfort and cooling energy. A coupling between Energy plus and CFD simulation (FLUENT) occurred to capture the effect of ceiling fan.	After the simulations, the results indicated that from the co-simulation model predicted cooler regions (lower PMV values) than EnergyPlus alone. The same applied in the cooling loads that were predicted by co-simulation model and EnergyPlus alone. Hence, apart from the results showing that Energy Plus seems to overestimate the results, the ceiling fan can deliver to the building with less cooling energy and improve the thermal comfort of the interior.

Table 5.3.2: Co-simulation of EnergyPlus and CFD simulation studies

5.4 EnergyPlus and CFD simulation methodology

The approach of a simulation, for the maximum possible result, differs depending on the purpose and use. In the previous paragraphs of this chapter, it is showed that Energy Plus and the CFD simulation have different capabilities and present different results, even if they were referred to the same understudy object. This occurs because different methodologies are followed, except for the different use of ventilation parameters. Methodologies that show some standard steps for both programs but differ in the parameters is taken into account. In the following paragraphs, there will be a presentation of the methodologies that are done in several surveys for both programs.

5.4.1 EnergyPlus methodology

The following methodology derives from the investigation carried out by various studies with various study objects (F. Calcerano et al., 2017; Fernandes et al., 2020; Figueira et al., 2014; Hong et al., 2019; Neves et al., 2011; Oropeza-Perez & Østergaard, 2014; Sorgato et al., 2016; Xiong et al., 2018; Zha et al., 2017b; Z. Zhai et al., 2011). Generally, the methodology is the same in all cases with the only difference being the natural ventilation strategy that was studied. The steps that occurred in EnergyPlus are as follows:

1. Weather data or climate data: This step a weather data is inserted in the software and it is essential to the overall study. The insights of the weather are derived by weather stations of Natural Institute of Meteorology of each country. This file will determine the outdoor conditions such as outdoor temperature, humidity, solar radiation, wind pressure, velocity and direction, etc. (files WMEC2, TMY2, etc.)
2. Building or model description: This step refers to the building's characteristics. Specifically, the user inserts information about the configurations of building elements such as U-values, airtightness, transparency, density etc. All this information in most cases are according to the local legislations or measurement were done with special equipment.
3. Internal heat gains and identify building uses: This step determines the internal heat gains, which can be emitted by lighting, equipment, people activities and thermal mass (some cases consider it). All the above are relative to the building uses, which is determined or separated in zones. It is obvious that the needs of

natural ventilation will be different for an office building or room and different for a residential building or room.

4. Develop design configurations: This step consist of different parameters that must be considered to meet the thermal comfort and thus the adjustment, which must be done to assess the building performance. It is important to determine the thermal comfort with respect to temperature, indoor air quality, humidity, internal heat gains, wind velocity and direction.
5. Airflow path study: The selection of the type of natural ventilation strategy to be used consists in this step. The required definition of the path that the air should make, from its entrance to space until its exit, is designed in this step. The prevailing air is also taken into account. In addition, the following are taken into account:
    a. mechanical ventilation or a hybrid system,
    b. night or day cooling,
    c. solar chimney or cooling tower.

   In many cases researchers use the Airflow Network in EnergyPlus platform, because it gives the opportunity to the user to design the airflow path.
6. Schedule ventilation: This step determines when the natural ventilation occurs. There are many capabilities that EnergyPlus provides to the user to schedule natural ventilation. Natural ventilation can be occurred depending on the indoor temperature and setpoint temperature. For instance, if the setpoint temperature is 24^{o}C and the indoor temperature is 26^{o}C, then natural ventilation will occur but if the indoor temperature is 23^{o}C, then natural ventilation will not occur. The same way occurs for the outdoor temperature or the difference of outdoor and indoor temperature. Everything are relative to the setpoint temperature, which in most cases is the comfort temperature. The results can be vary relative to the occupants', lighting, equipment and HVAC (in case of hybrid ventilation) schedule.
7. Select type and size of ventilation device: In this step, the designer predesigns the ventilation devices. Ventilation devices are those that contribute to the natural ventilation process. The type of these devices can be windows, louvres and doorways, solar chimney or cooling tower, trickle vents, any other passive tech-

nique and mechanical fan devices. The size of them will affect the performance of the wind drive effect and the buoyance effect.

8. Results and analyze the design: In this step, the designer assesses the results and attempt to do some adjustments to address better results or better observations. There are many ways to assess the results to make some conclusions. One of them is comparing the building with a reference building, which has standard characteristics. Another way is by a real measurement, which occur during experiment under certain, or not conditions. A last one is a comparison of previous studies, which maybe the researchers omit some coefficient or did other assumptions. The results are assessed in most cases as energy savings (kWh/m^2), or in airflow rate (ACH or m^3/s)(Z. Zhai et al., 2011) or in hours of thermal comfort that the natural ventilation provides (Xiong et al., 2018).

These are the main steps that researchers take in the aforementioned literature references and many others so that they can study and evaluate the possible application of natural ventilation potential. As it is mention, the EnergyPlus has some drawback relative to results, which sometimes overestimate the outcomes. In the next paragraph will be discussed the steps of CFD simulation.

5.4.2 CFD simulation methodology

In CFD simulation software the methodology is used by the researchers is similar to that of EnergyPlus. The only difference is that some parameters require to be more precisely in order for the program to perform correctly. More analytical are presented in the following steps according to the studies (Allocca et al., 2003; Ferrante & Cascella, 2011; Mora-Pérez et al., 2016; Nugroho et al., 2006; Ohba & Lun, 2010; Spentzou et al., 2019; Visagavel & Srinivasan, 2009; B. Wang & Malkawi, 2019):

1. Weather data/ climate data: In this step, the same as EnergyPlus, the conditions are determined according to the local conditions (National Institute Meteorology of each country or location). If a research desires and has some measurements, he/she can inserted information even for the neighborhood where the understudy building is located. The main climatic parameters are wind velocity, wind direction and temperature, which constitute the boundary conditions. In addition, the user must determine the macroclimate conditions, which are presented in a 3-D

box. The difference compare with the EnergyPlus, the determination of the climatic conditions can be exhausted and needs the user to be aware.

2. Surrounding buildings or objects (vegetation etc.): In this step, the surrounding buildings or objects are determined. The disadvantage of the EnergyPlus in this step, the user inserted building only for shading influence. In contrast, CFD simulation calculate the shading, wind velocity and direction, which are affected by the shape, distance and the volume of the surrounding buildings.
3. Building or model description: This step concern only the building's shape, because this software does not calculates energy consumption, so the U values of the elements are not taken into consideration.
4. Internal heat gains and identify building uses: This step is the same as the EnergyPlus. The determination of the internal heat gains, which are occupants' activities, equipment, lighting and thermal mass, are considered. The user can divide the building in numeral zones if he/she desired.
5. Develop design configurations: In this step, it is the same with the EnergyPlus, the designer inserted the thermal comfort conditions in order to assess the results.
6. Airflow Path study: This step is the same with the EnergyPlus; the designer can set the path that the air will takes. In additions, the user can inserted internal object for more detailed results in order to see if the order of things could affect the results.
7. Schedule ventilation: In this step, the user determines the specific time and period in which the natural ventilation will occur. In contrast with EnergyPlus, the user should change the setting in order to obtain a full picture of the natural ventilation strategy. For instance, the ventilation will occur at 11:00 in the summer period 20th of June in CFD simulation, but in EnergyPlus occurs annually and provide the user with a full report for each day of the year. CFD simulation is more manual software.
8. Select type and size of ventilation device: This step is the same with the EnergyPlus, in which the user describes the features of the ventilation devices.
9. Type of ventilation strategy: In this step, the user determines the type of ventilation he/she will exam. That happens, because different parameters must be de-

termined for the buoyance drive and wind drive ventilation strategy. Moreover, the different pressure that occurs indoor and outdoor of the building influence the performance differently. In most cases are calculated separately to gain time.

10. Results and analyze the results: In this final step, the assessment of the results is occurred. The results were compared with experimental results or/and other studies and real measurements. The values in most studies that are investigated are the indoor wind velocity (m/s) and direction, the indoor wind turbulence, the indoor temperature (^{o}C) and stratification (Nugroho et al., 2006; Spentzou et al., 2019), the wind pressure (Pa) around the building, and the coefficient of heat transfer and pressure. In some case, the evaluation was done by the hours that can provide comfort conditions (B. Wang & Malkawi, 2019).

These are the main steps that the researches did in order to predict the natural ventilation potential. The different numerical approaches that are used broadly (Hosain & Fdhila, 2015; Khalil, 2012; Visagavel & Srinivasan, 2009; B. Wang & Malkawi, 2019) are categorized as Reynolds-Averages Navier-Stokes, (RANS), Large Eddy Simulation (VLES), Detached Eddy Simulation (DES), Boussinesq and others.

5.4.3 Coupling EnergyPlus and CFD simulation programs

In this paragraph, according to what was analyzed above for the methodologies of the two programs and with the analysis of their differences (subsection 5.3), will be described the methodology that these two programs are combined. The combination of these two programs can provide the user with more precise and reliable results for a better evaluation. The steps of their methodology do not differ significantly from what was described above. The only discrepancy occurs when the outputs of one program must be inserted into the latter program and vice versa. The methodology, which is followed by most studies (Dorer et al., 2013; El Ahmar et al., 2019; Malkawi et al., 2016; Pappas & Zhai, 145 C.E.; Performance et al., 2018a; Raji et al., 2020; Shan et al., 2020; Shen & Wang, 2020; Webb, 2013; Yi & Malkawi, 2011; Z. Zhai & Chen, 2003; Z. J. Zhai & Chen, 2006; R. Zhang et al., 2013a), is the subsequent:

1. Weather data or climate data: In this step, the climatic conditions are inserted in the EnergyPlus software to determine the boundary conditions for the CFD simulation program. The values that inserted in the CFD simulation for the determi-

nation are temperature (surface temperature, outdoor temperature, indoor temperature), wind direction, wind velocity and solar radiation. The CFD will calculation the stratification temperature in the indoor environment, the air change per hour and wind pressure, which are significant factors for the natural ventilation performance in the buildings.

2. Surrounding buildings or objects: This step refers only to the CFD simulation program. As it was described above, the surrounding obstacles are calculated in more detail in CFD. The EnergyPlus has as a choice urban or country or terrain etc., which rely on empirical insights.
3. Building or model description: In this step the building characteristics are inserted in both programs but as it was described above, because each program calculates different parameters.
4. Internal heat gains and identify building uses: In this step consist of the internal heat gains derives from the lighting, equipment, thermal mass and human activities relative to the buildings uses. In both programs are inserted in order to set the boundaries for the understudy model.
5. Develop design configurations: In this step, legislations and surveys are inserted to determine the thermal comfort conditions for the model that is examined. Thermal comfort conditions, for the CFD simulation, are important to predict the best contribution of each natural ventilation. As for EnergyPlus, thermal comfort, after the iterative simulations from CFD, will determine the energy consumption of the building with the best-chosen option.
6. Airflow Path study: This step is the same with the above airflow path, but in CFD simulation the results are more accurate and these results are inserted in the EnergyPlus for the final calculations.
7. Schedule ventilation: In this step, result for EnergyPlus are inserted in CFD simulation. Specifically, it is inserted the exact time and period for the worst-case scenario, which was exported by EnergyPlus, in the CFD simulation software to calculate the temperature, airflow rate and thermal comfort indexes (like PMV). The results of the CFD simulation are inserted to the EnergyPlus for more accurate results.
8. Select type and size of ventilation device: This step is the same for both, in which the user describes the features of the ventilation devices.

9. Type of ventilation strategy: In this step, the user determines the type of ventilation he/she will exam. In CFD simulation the buoyance drive and wind drive ventilation strategy are examined separately and the results of that process are inserted in the EnergyPlus. Moreover, in wind driven case the model is considered as isothermal and the results of wind speed and pressures are obtained. In buoyancy driven case it is assumed that there is no air and the results are for the stratification of the temperature and the thermal comfort of the occupant(s).
10. Results and analyze the results: In this step, the final decision is taken. The EnergyPlus is used to provide to the user the results after this procedure. In reality, in every above step, the engineer should assess the results but in this step he/she will obtain the full picture. The results are compared with a reference building or experimental results or results from other studies. The measure, which aid the engineer to evaluate the natural ventilation strategy, is the energy consumption or performance (kWh, kWh/m^2) of the model or building.

This is the main methodology that is followed by many researchers to obtain the best results and the most reliable. There are some software (c++, matlab, designbuilder, etc.) that aid to pair these two programs so that the process takes less time and the avoidance of errors in data transfer.

6 Building- Case studies

6.1 Natural ventilation potential in three Mediterranean countries

Evangelos Grigoropoulos, Dimitrios Anastaselos, Sandro Nizetic and Agis M. Papadopoulos conducted a research about natural ventilation for a NZEB residential building in Mediterranean Climate (Grigoropoulos et al., 2017). This study has as an objective to provide insights about the impact of ventilation strategies. Strategies that were implemented in NZEB in order to assess the contribution of natural ventilation as a passive cooling technique.

Different software were applied to calculate the various passive cooling techniques. The software are:

- Energy Plus 8.0 for the calculation of the energy performance of the model
- SketchUp 3D software for the model designing
- OpenStudio project for the specification of the building materials, construction, schedules and thermostats.

The methodology that they used is the same as it was described in previous chapter. Thus, the steps that they followed are:

1. Climate data: The climate data were inserted in EnergyPlus software and was about Mediterranean region. The locations that they have selected were Athens, Larnaca and Thessaloniki. Thus, different weather data was corresponded for each location.
2. Surrounding buildings were not considered
3. Building or modeling description: In this case, the model is a residential building, south and north oriented and consisting of net conditioned area of 150 m^2 and volume of 502 m^3. On the external side of the envelope was implemented a 25 cm layer of extruded polystyrene (XPS), in order to eliminate the thermal bridges. The terrace was insulated by a 30 cm of XPS insulation material and floor with 16 cm of the same insulation material. As for the windows, low e double glaze were installed and solar heat gain coefficient was at low levels

(0.33). The airtightness of the building was at very low levels, 0.1 ACH. All the selections were according to European and ASHRAE directive. Heat pump air to water (COP=4.55) was used as HVAC system for heating and cooling. The rest energy demand was covered by a monocrystalline photovoltaic system.

4. Internal heat gains and identify building uses: The model was separated in five different zones depending their orientation and heat gains. The internal heat gains from the occupants, lighting and electric equipment were considered.
5. Develop design configurations: In this stage, the indoor design conditions were determined according to prEN 15251.
6. Airflow path study: The strategies that were selected for this research are the scale up of ventilation rate, variations of ventilation schedule and implementation of hybrid ventilation. For the first, a steady increase of ventilation rate up to 8 ACH was investigated. For the second, different ventilation schedule, five scenarios were calculated according to the occupancies appearance. For the last strategy, a hybrid ventilation system was studied in order to exam the case of the days at which not outdoor air has enough velocity.
7. Schedule ventilation: In this step, researchers assume that the occupancy and their activity are turn of during 08:00-17:00 on weekdays. As for the first strategy natural ventilation was provide at night (22:00-24:00) and early in the morning (06:00-08:00). Moreover, natural ventilation was ceased when the outdoor dry bulb temperature surpass indoor zone temperature, to avoid excess energy for heating.
8. Select type and size of ventilation device: The devices, that have been used to provide natural ventilation, were openings for the first two strategies. As for the third, an incorporation of HVAC system with the aforementioned was considered.
9. Results and analyze the design: The results were presented and commended in this step. The parameters that were used to evaluate the results, were cooling primary energy in kWh/m^2 and overheating degree hours in hours (h). All the results were compared with a base case scenario (reference building).

The results from this survey showed that natural ventilation could contribute to the minimization of cooling energy consumption and let alone in total primary energy. Specifically, the results from the first strategy showed a reduction of approximately 10% for the three cities (Athens, Larnaca, and Thessaloniki). As for the second strategy, by changing the ventilation schedule, the results showed an increase of the daytime ventilation and night ventilation. Specifically, a decrease of primary energy was observed in all scenarios, reaching up to 4% at night ventilation (2% for the case of 22:00-07:00 with 2ACH, 3%-4% for the case of 22:00-07:00 with 8ACH). The application of higher ventilation rate caused a reduction of overheating degree hours about 50% for the case of Athens and 30% for the case of Larnaca. At the last strategy of hybrid ventilation, it was observed an increase of electricity consumption and lead to more primary energy up to 20%, but it provides more pleasant environment.

6.2 Single sided and cross ventilation combined with thermal mass in Mediterranean area

The study that was conducted by Filippo Calcerona, Carlotta Cecchini, and Letizia Martinelli (C. Calcerano, 2014), has as an object to assess single sided ventilation and cross ventilation coupled with two types of thermal mass. The objective is to evaluate the contribution of natural ventilation and thermal storage relative to the energy consumption reduction in three different location of Italy. The four locations are Rome, Naples, and Messina.

The software that they have used in order to simulate their different scenarios was EnergyPlus.

After explaining the meaning of the thermal mass and natural ventilation strategies, they did the following methodology:

1. Weather data or climate data: They consider three different climatic conditions corresponding to each city. Generally, the climate in Italy based on Mediterranean climatic conditions. Thus, most of these conditions are the same as the Greek climate. The summer period was the understudy conditions.
2. Building or model description: An airtight building model (o,5ach infiltration) was designed with a south facing. Medium U values for the external opaque elements were considered, but the windows had low enough U value.
3. Internal heat gains and identify building uses: They determined the internal heat gains, which can be emitted by lighting, equipment and people activities. Thermal mass as part of the investigation was inserted. Two types of external concrete were assumed, depending on their thermal mass capability. Model A for a

medium-light structure (18 cm thickness) and Model B for a heavy structure (30 cm thickness). All the other surfaces were assumed adiabatic.

4. Develop design configurations: As thermal comfort, they assumed the adaptive model according to $T_o = 0.33T_e$ (external temperature) + 18.8ºC ± 3ºC with 80% acceptability. They had defined the occupancy schedule inside the zone.
5. Airflow path study: They used Airflow Network in order to implement the different strategies. Also a dynamic multi zonal numerical simulation was implemented too. For the single sided ventilation was implemented a large window. As for cross ventilation two windows at opposite directions were designed.
6. Schedule ventilation: Ventilation control mode was used and programmed based on the temperature difference between indoor and outdoor temperature (if $T_{room} > T_{out}$, and T_{room}> summer setpoint temperature 21°C). An opening factor for windows were set at 0.5, with T_{room} and T_{out} difference lower and upper limit set to 5 °C and 10°C.
7. Select type and size of ventilation device: Two different types of natural ventilation strategies were examined. They are the followings:
   a. Single sided Ventilation (SSV)
   b. Cross Ventilation (CV)
8. Results and analyze the design: The results were presented in this step. The evaluation of the results were occurred according to hygrothermal comfort and energy consumption. The first, the index is the Discomfort hours Reduction Potential (DRP) and expresses the percentage of the discomfort hours that reduced due to the used natural ventilation strategy. The latter, the index is the energy consumption reduction potential (ERP) and expresses the reduction in percentage of energy consumption for cooling. It must be highlighted that the Discomfort Benchmark simulation expressed in hours per year (h/y) and Energy Benchmark Simulation (EBS) expressed in kWh/m^2 y.

The results showed that both natural ventilation strategies provoked reduction of the discomfort hours and primary energy consumption for cooling. The highest reduction of DRP was observed in Rome. The reduction for SSV was 97% and for CV 95%. In the case of energy savings, the implementation of cross ventilation had attained a reduction of 80% in contrast to single-sided ventilation at the same location. Generally, the reduction for DRP fluctuated from 39% to 97% and for ERP from 21% to 80%. In addition, buildings with higher thermal storage had better performance in both natural ventilation strategies compare with medium-low thermal mass buildings. Thus, except for the natural ventilation strategies that can be implemented in Mediterranean countries, thermal mass is another advantage for buildings with high levels.

6.3 Different passive strategies for natural ventilation in Italy

The study that was conducted by Filippo Calcerona, Carlotta Cecchini, and Letizia Martinelli (F. Calcerano et al., 2017), has as an object to assess six different passive strategies coupled with two types of thermal mass. The objective is to evaluate the contribution of natural ventilation and thermal storage relative to the energy consumption reduction in four different location of Italy. The four locations are Rome, Naples, Messina and Catania.

The software that they have used in order to simulate their different scenarios was EnergyPlus.

After explaining the meaning of the thermal mass and natural ventilation strategies, they did the following methodology:

1. Weather data or climate data: They consider four different climatic conditions corresponding to each city. Generally, the climate in Italy based on Mediterranean climatic conditions. Thus, most of these conditions are the same as the Greek climate. The summer period was the understudy conditions.
2. Building or model description: An airtight building model was designed with a south and north orientation. Medium U values for the external opaque elements were considered, but the windows had low enough U value.
3. Internal heat gains and identify building uses: They determined the internal heat gains, which can be emitted by lighting, equipment, people activities and thermal mass. Two types of external concrete were assumed, depending on their thermal mass capability. Model A for a heavy structure (30 cm thickness) and Model B for a medium-light structure (18 cm thickness). All the other surfaces were assumed adiabatic.

4. Develop design configurations: As thermal comfort, they assumed the adaptive model according to $T_o = 0.33T_e$ (external temperature) + 18.8ºC ± 3ºC with 80% acceptability. They had defined the occupancy schedule inside the zone.
5. Airflow path study: They used Airflow Network in order to implement the different strategies. Also a dynamic multi zonal numerical simulation was implemented too.
6. Schedule ventilation: Ventilation control mode was used and programmed based on the temperature difference between indoor and outdoor temperature (if $T_{room} > T_{out}$, and $T_{room} >$ summer setpoint temperature 21°C). An opening factor for windows were set at 0.5, with T_{room} and T_{out} difference lower and upper limit set to 2 °C and 10°C.
7. Select type and size of ventilation device: Six different types of natural ventilation strategies were examined. They are the followings:
    a. Single sided Ventilation (SSV)
    b. Cross Ventilation (CV)
    c. Inlet wind tower (IT)
    d. Thermal Chimney (TC)
    e. Evaporative cool tower (CT)
    f. Earth pipes (EP) (It is not subject of this dissertation)
8. Results and analyze the design: The results were presented in this step. The evaluation of the results were occurred according to hygrothermal comfort and energy consumption. The first, the index is the Discomfort hours Reduction Potential (DRP) and expresses the percentage of the discomfort hours that reduced due to the used natural ventilation strategy. The latter, the index is the energy consumption reduction potential (ERP) and expresses the reduction in percentage of energy consumption for cooling. It must be highlighted that the Discomfort Benchmark simulation ex-pressed in hours per year (h/y) and Energy Benchmark Simulation (EBS) ex-pressed in kWh/m2 y.

The results showed that all natural ventilation strategies provoked reduction of the discomfort hours and primary energy consumption for cooling. Better performance obtained with CV, IT and TC strategies. In addition, buildings with higher thermal storage had better performance in all natural ventilation strategies compare with medium-low thermal mass buildings. Thus, except for the natural ventilation strategies that can be implemented in Mediterranean countries, thermal mass is another advantage for buildings with high levels.

6.4 Case study of solar chimney in Athens, Greece

I.P. Koronaki carried out a study about the impact of different features and orientation of solar chimney in Athens (Koronaki, 2013). Three different types of solar chimney (SC) were compared, integrated on a model building. The selected location was in Athens suburbs and the July 15 was day that the SCs were exposed. The day was chosen because obtains the warmest nights in Mediterranean regions. The software that the researcher have used in order to simulate their different scenarios was EnergyPlus v6.0.0.023.

After explaining the different studies were conducted, the benefits that SC has compare to cross ventilation and the operational ability of SC, Koronaki did the following methodology:

1. Weather data or climate data: Weather data that was utilized referred to real Athens weather data. This data included solar irradiance, dry and wet buld air temperature, in order to insert enough information. Information of the factors that affects solar chimney performance.
2. Building or model description: The model was a single zone with open plan floor and rectangular shape. The dimensions of it, length 10 m, width 6 m and height 3m. It had openings in all facades but most of them accommodated at the south façade. South orientation for the model was used. The envelope assumed insulated and consisted of heavy structure materials, such as concrete, reinforced concrete, bricks etc. Thus, the U-values of the elements generally were at low levels. ASHRAE legislation was used.
3. Internal heat gains and identify building uses: Internal heat gains of four occupants and 300W electric equipment were considered. The zone was studied as a residential building.
4. Develop design configurations: In this study, the thermal comfort conditions were taken into account respect PMV, PPD and TSENS indexes. An adjustment

of the solar chimney model was occurred with an experimental measurements and other studies.

5. Airflow path study: The path was the inlet air entrance from the façade windows and exits through the duct of solar chimney. After research of many studies, Koronaki conclude to a specific value of discharge coefficient. The Airflow Thermal Chimney was used in EnergyPlus platform.
6. Schedule ventilation: The solar chimney operated, according to ventilation schedule, between 21:00 and 06:00. Koronaki scheduled the clothing factor, activity, room occupancy and electric power consumption, to provide results that are more realistic.
7. Select type and size of ventilation device: As it is mentioned, SC's effectiveness was examined in this study. Three different SCs were designed SC1, SC2 and SC3 (Figure 6.4.1, Figure 6.4.2, Figure 6.4.3)

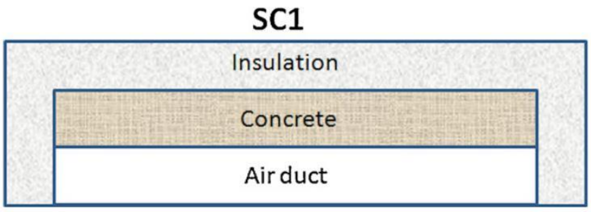


Figure 6.4.1: Layers of SC1 (Koronaki, 2013)

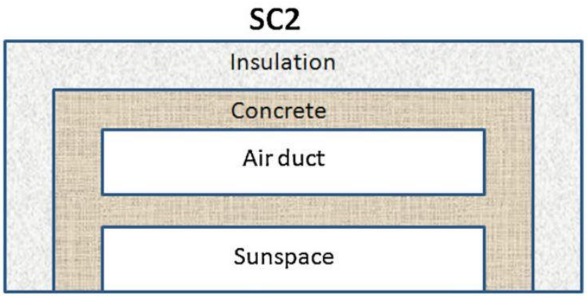


Figure 6.4.2: Layers of SC2 (Koronaki, 2013)

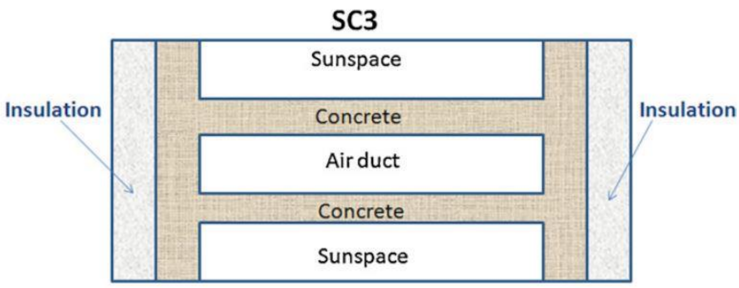


Figure 6.4.3: Layers of SC3 (Koronaki, 2013)

Different parameters were investigated to find the best solar chimney structure. These parameters were:

a. Absorber concrete wall thickness of 10 cm and 15 cm
b. Duct air gap of 10 cm, 15 cm and 20 cm
c. Duct wall height of 1 m, 2 m, and 3 m
d. Solar chimney orientation South, West and East.
e. Glass and acrylic cover

The combinations of these parameters were calculated with respect of the following scenarios:

a. night-time duration and strength of stack induced ventilation
b. diurnal channel glass and wall inner surface temperatures for different orientation,
c. nocturnal air temperature difference between indoor space and outdoors
d. fan energy savings
e. cooling effectiveness factor

8. Results and analyze the design: The results of various scenarios were presented in this step. For each scenario was used different or same units. As a main unit was used the mass flow rate (kg/s) for scenarios a, and c, for scenario b incident sola irradiance (W/m^2), a ranged of 3.00 to -2.50 for the thermal comfort indexes, for scenario d kWh/day (/month). As for scenario cooling effectiveness factor (%) is considered. Thus, the assessment was occurred with these values.

The results indicated that SC2 with West orientation had better performance in buoyance driven effect. In case of thermal comfort, SC1, west oriented, achieved better performance. Koronaki found that an increase of the concrete thickness can provide better performance. Moreover, the height of the chimney has more significant role than width. Finally, a significant reduction of electric energy (56kWh/month for this study) and cooling energy reduction up to 32% can be obtained with the SC2 and dimensions (L=6m, H=3m, d=0.2m, t=0.1m and west oriented).

6.5 Case study of evaporative cooling tower integrated on a plus energy residential building.

Francesco Babich and his colleagues (Babich et al., 2017) investigated the natural ventilation potential by integrating an evaporative cooling tower on a high-performance residential building. The building was tested in eight different European locations and one location in the USA. Specifically, the eight European locations were three from Spain (Cordoba, Seville, and Zaragoza), two from Greece (Athens, Thessaloniki), one from Portugal (Evora), and two from Italy (Catania, Foggia). As for the USA, the location was Phoenix. Dynamic thermal modeling was used for the energy cooling consumption results and CFD software for the evaporative cooling tower assessment. These two software were coupled to pro-vide results that are more realistic.

After explaining the functionalities of evaporative cooling tower and natural ventilation strategies, they did the following methodology:

1. Weather data or climate data: They consider nine different climatic conditions corresponding to each city, as it was explained previously. Generally, the prevailing climate in the eight European countries is Mediterranean while for Phoenix it is close to it but warmer and dryer. The summer period was the main element for the study.
2. Building or model description: A high performance residential building was designed, known as plus energy house. These type of buildings are low energy dwellings and their annual energy balance is positive. The key to their high end performance are the passive techniques that are used. These passive techniques are combined with renewable energy sources, such as PV panels. Very low U values for the external opaque elements were considered. The same applies for the windows (triple glazing).
3. Internal heat gains and identify building uses: They determined the internal heat gains, which can be emitted by lighting, equipment, people activities and thermal mass. The thermal mass capability was considered. In this plus energy house the PCM (Phase change materials) was used.
4. Develop design configurations: As thermal comfort, they assumed the setpoint temperature at 26^{o}C. They had defined the occupancy schedule inside the zone.

5. Airflow path study: An inlet passive downdraught evaporating cooling tower was implemented in this building. This means that the outdoor air with the dry bulb temperature is inserted from the top of the tower by obtaining wet bulb temperature from the evaporative mechanism. Then the air flows through the chimney, distributed in the indoor space, and finally, exits from the windows.
6. Schedule ventilation: Ventilation control mode was used and programmed based on the setpoint temperature 26ºC. Specifically, when the indoor temperature is above the setpoint temperature the system operates and when the indoor temperature is below the setpoint temperature does not operate.
7. Select type and size of ventilation device: Evaporate cooling tower was selected with 1.2m height above the roof.
8. Results and analyze the design: The results were presented in this step. The evaluation of the results were occurred according to set point temperature and energy consumption. The results of energy consumption were measured in kWh.

The results showed that the evaporative cooling tower was beneficial for all Mediterranean locations and for the Phoenix. Specifically, by implementing the maximum ACH ($6.9h^{-1}$) in DTM the cooling tower satisfies up to 43% of the energy cooling demand in the summer period. For the rest European locations, the energy savings are 47% for Cordoba, 35% for Seville, 52% for Zaragoza, 38% for Thessaloniki, 47% for Evora, 45% for Catania, and 46% for Foggia. The results show that an implementation of such a passive system could contribute positively to upgrade a building for lowering cooling energy consumption.

6.6 Case study of small residential buildings in Mediterranean region

An interesting study was carried out by Marco S. Fermandes et.al. (Fernandes et al., 2020), which analyses and assesses the impact that three parameters of natural ventilation may have on the energy performance of dwelling. The research concentrates on the implementation of natural ventilation, in cooling terms, on a large number of residential buildings in different climate locations. For the calculations they used EnergyPlus v.9.0.1.

After explaining the functionalities of natural ventilation strategies and especially night ventilation, they did the following methodology:

1. Weather data or climate data: They studied sixteen different climatic conditions, which are directly affected by the Mediterranean climate. The sub-study countries are located near the coasts of the Mediterranean Sea. The climatic data they used are for areas of Southern Europe, North Africa, and the Middle East. They investigated both summer and winter period to analyze the impact in cooling an heating energy.
2. Surrounding buildings were not included.
3. Building or model description: A two story family residential building consisting of a living room, a hall and a bathroom on the first (ground) floor, and a corridor, master bedroom, a double bedroom, a single bedroom and a bathroom on the second floor. The variable building designs, 500 alternative building solutions precisely, each of them satisfy the same geometric and topologic requirements. The exterior opaque and transparent elements had the U values of another work that they had done **(**Error! Reference source not found.**)** (Fernandes et al., 2019). Generally the exterior opaque elements were insulated and their U values were low enough (Uvalue <0.65 $W \cdot m^{-2} \cdot K^{-1}$). The U values for the exterior windows fluctuates from 0.40 $W \cdot m^{-2} \cdot K^{-1}$ to 2.60 $W \cdot m^{-2} \cdot K^{-1}$. The highest values were used in Alexandria, Egypt. The solar heat gain coefficient for windows was equal to 0.6.
4. Internal heat gains and identify building uses: They determined the internal heat gains, which can be emitted by lighting, equipment, people activities and thermal mass. The HVAC systems (Ideal loads air system) were implemented. Dif-

ferent thermal zones for the building were determined. Shading devices were inserted in the calculations.

5. Develop design configurations: As thermal comfort, they assumed the setpoint temperature at 20°C for heating period and 25°C for cooling period, for all cases. They had defined the occupancy schedule inside the zone.
6. Airflow path study: An airflow through windows were taken .
7. Schedule ventilation: The schedule for natural ventilation operation was determined according to the design setpoint temperature for each period. In particular, when the internal temperature is lower than the minimum setpoint temperature (Tmin), then the natural ventilation is shut off. In addition, they determined when the temperature difference (ΔT) between the indoor and outdoor temperature is higher than the setpoint then again natural ventilation stops to operate. The various airflow rate fluctuates from 0.1 ACH to 30 ACH. Tmin ranges from 21°C to 25°C and ΔT varies from 1°C to 3°C. The same idea applies for night ventilation with combination of Tmin>20°C and ΔT>0°C.
8. Select type and size of ventilation device: The devices are the windows of the dwelling and the size of them are not mentioned.
9. Results and analyze the design: The results were presented in this step. The ventilation parameters that were evaluated and combined are air change rate, minimum indoor setpoint temperature, and the difference of indoor and outdoor temperature. The objective of these parameters is to minimize the energy consumption. The results of energy consumption were measured in kWh.

The results indicate that variation of ACH, Tmin and ΔT had different influence. Specifically, the higher ACH they introduced in the software the better results they achieved. As for the Tmin the optimal temperature was 24oC and the ΔT the lower values the better results. These results are relevant to the occupants and the thermal comfort. High rate of ventilation (ACH) makes occupants feel comfortable, because of evaporation, and Tmin=24°C is the temperature most of the studies agree with. The researchers conclude that ventilation can contribute to a beneficial way in order to achieve for the Mediterranean climate better energy performance of the buildings. The results showed that the higher reduction was attained when they set at 30 ACH, a Tmin equal to 24°C, ΔT=1°C and infiltration 0.1ACH. The reduction for all cases and previous settings fluctuates between 31.3% and 85.2% annually. The energy that was reduced the most was cooling energy reduction as the researchers observed.

6.7 Case study of NZEB residential building in Italy

From the first chapter of this dissertation, it was clarified from now on the new buildings should be constructed with low energy requirements, consumptions, and low carbon dioxide emissions. The use of passive systems and techniques can contribute to achieving these objectives. Energy efficient technologies can be applied or/and integrated to construct a building with low energy and high thermal performance. This case study was included because it is interesting in the case of a buildings complex that apply natural ventilation in NZEB buildings.

A. Ferrante and M.T. Cascella (Ferrante & Cascella, 2011) studied NZEB model building blocks in Italy by integrating natural ventilation strategies (cross ventilation and buoyance effect).

The understudying building is located at the peri-urban area in Tricase, in Puglia, in the south of Italy. Generally, they described the location, where the buildings are old and mostly were built between 1960 and 1970. In that period the residential buildings were in high demand. Hence, owners of that building confront the problems of overheating in summer and heat losses in winter. Therefore, researchers were affected by the main problem of Tricase residents, they set up a fragmented and isolated building blocks in low or no urban density space (Figure 6.7.1 and Figure 6.7.2).

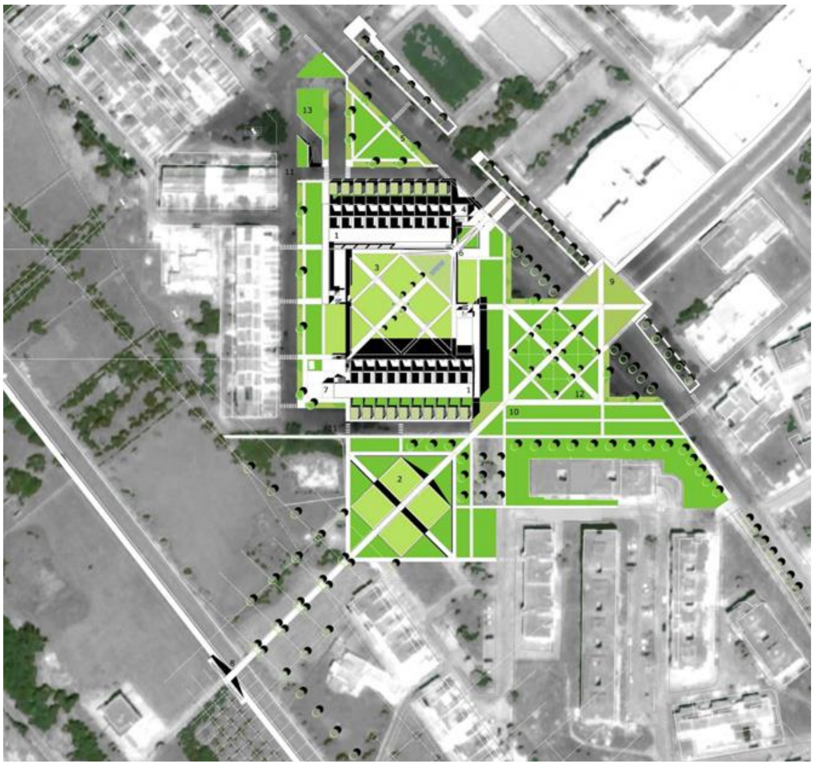


Figure 6.7.1: Panoramic image of the building blocks model Source:(Ferrante & Cascella, 2011)

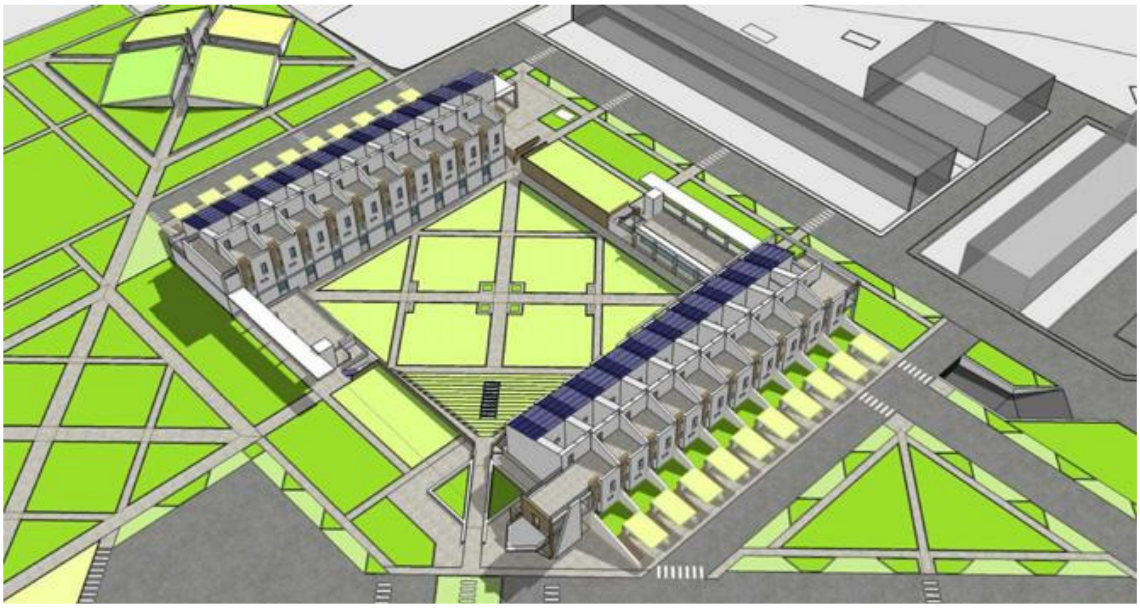


Figure 6.7.2: Closest view of building blocks model Source:(Ferrante & Cascella, 2011)

The selection and design method was influenced by the subsequent criteria:

- South orientation
- Catching summer breeze for natural ventilation
- Provide protection to the buildings from the prevailing wind in winter

The model building, that is simulated, were designed with simple plan based on the above principles. In addition, high thermal energy performance bricks were integrated. The zones were divided according to their own environmental conditions to achieve both efficient energy performance and indoor thermal comfort. Overhangs and shading devices were considered, depending on winter and summer solar gains. Moreover, the high inertia of the structure and reflective materials were calculated to improve the thermal performance of the building.

Cross ventilation through external surfaces and courtyard in combination with vertical air extraction (ducts and solar chimney) underneath the PV system were designed to obtain exploitation of natural ventilation (Figure 6.7.3, Figure 6.7.4).

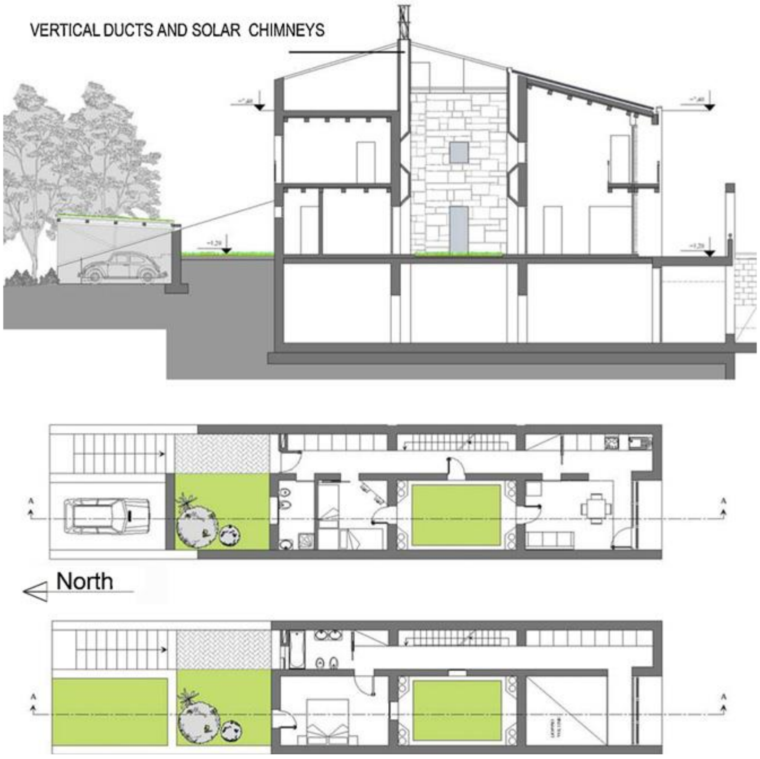


Figure 6.7.3: Plans and section of the model building Source:(Ferrante & Cascella, 2011)

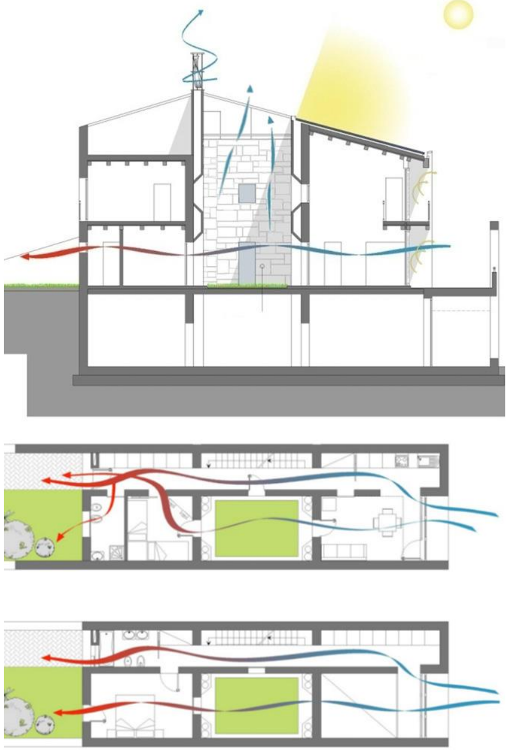


Figure 6.7.4: Cross ventilation and vertical extraction (duct and solar chimney) Source:(Ferrante & Cascella, 2011)

After the calculations (used Ansys CFX v.10.0 software) of these features and natural ventilation strategies, the results showed a very high energy performance building with no plant system, which heating primary energy demand is equal to 17.96kWh/m^{2}y and for cooling primary energy demand is 22.10 kWh/m^{2}y. Another scenario was to use hybrid ventilation system, when the natural ventilation was not enough to obtain thermal comfort, then a heat pump system with VRF (Variable Refrigerant flow) external unit activated to provide comfort indoor conditions. Finally, the researchers concluded that the air movement through all rooms, natural ventilation can provide to the users a soft cooling effect and further energy saving in the summer period (Figure 6.7.5). The results indicated, the energy performance that these implementations has achieved are significant. The energy consumption either for heating or cooling is at low level annually. It seems that natural ventilation techniques can contribute significantly in the overall thermal energy savings of the dwelling.

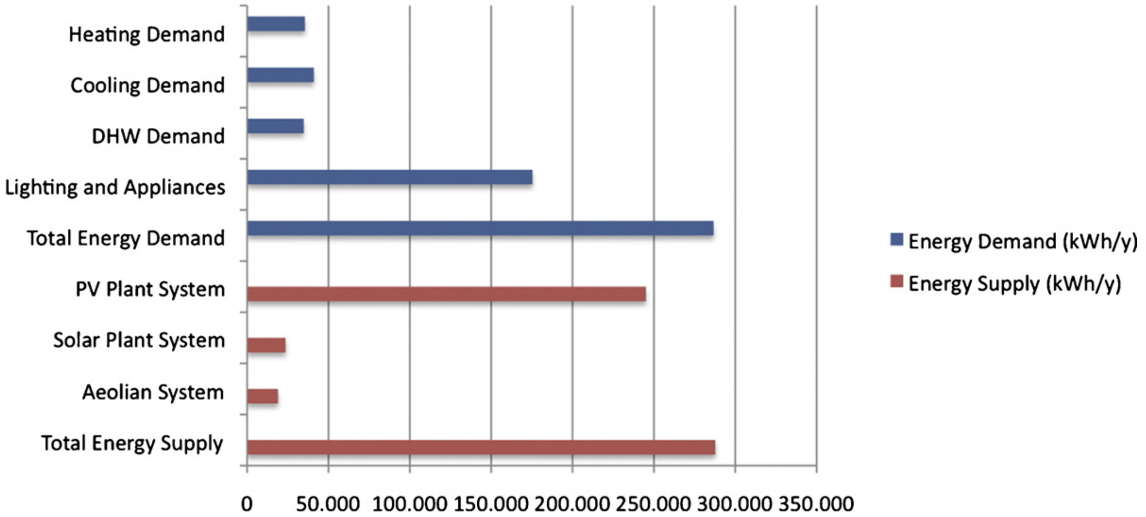


Figure 6.7.5: Energy demand and energy supply of the model building annually Source:(Ferrante & Cascella, 2011)

7 The contribution and effectiveness of each technique

In the previous chapters, a general description was made of what is natural ventilation of buildings, how it can be created, what techniques exist, how they are affected, the software that are used, and what methodologies are followed. In this chapter an evaluation, a brief and comparative analysis of various examples will be made. The contribution of natural ventilation and the effort to reduce the cooling loads of a residential building will be analyzed, too. The following studies and more are gathered at the **Table 7.1**.

Athors		Mora-Perez et. al.	Visagavel et. al.	Allocca et. al.	Sumei Liu et. al.	Nie et. al.	Rilatupa	Haase, Amato	AbdelRahman	Fadzil et. al.	Gagliano et. al.	Ciaran McCabe, Susan Roaf	Ben Richard Hughes, S.A.A. Abdul Ghani Sheffield	Babich et. al.	Santamouris et. al.	Geros et. al.	Gratia et. al.	Grigoropoulos et.al.	Koronaki, I. P.	X. Zha et. al.	Alexandre Patouparvedy, Milan Despotovic	Pisello	Ji et. al.	Calcerano et. al.
Year		2016	2016	2002	2013	2015	2019	2009	2017	2010	2014	2013	2010	2017	2010	1999	2004	2017	2013	2017	2013	2016	2012	2017
Geographphincal context		Valencia, Spain	Tiruchengodu, India	Boston, USA	Chongqing, China	Changsha, China	Cawang, Indonesia	Twelve regions, China	New Damietta, Egypt	Penang, Malaysia	Catania, Italy	Dubai, United Arab Emirates	United Kingdom	South European Countries	Athens, Greece	Athens, Greece	Uccle, Belgium	Greece, Cyprus	Athens, Greece	Shangai, China	Belgrade, Serbia	Three regions, Italy	Seven regions, China	Four regions, Italy
Climate	Mediterranean	√						√			√			√	√	√		√	√			√		√
	Similar			√	√	√		√	√			√								√	√		√	
	Other		√				√	√		√			√				√						√	
Building type	Residential		√	√	√	√		√	√		√	√		√	√			√	√		√	√		√
	Office															√	√						√	
	Other	√					√			√			√							√				
Methods of study	Experimental: Full scale						√		√	√			√		√	√								
	Experimental: Small scale																							
	Theoritical: E+				√									√				√	√	√	√	√	√	√
	Theoritical: CFD	√	√	√	√				√			√	√	√										
	Theoritical: Other				√	√	√	√		√	√	√		√	√	√	√							
Area of the building (m^2)	0-50		√	√			√			√											√			
	50-100	√			√										√				√					√
	100-200					√												√		√		√		
	200-5000								√		√	√			√	√	√							
Insulated	Full insulated*	√												√	√		√	√		√		√	√	√
	Partially insulated**					√					√								√					
	Not mentioned		√	√	√		√	√	√	√		√	√			√					√			
Airtightness	Included	√									√			√	√		√	√		√	√	√	√	√
	Not mentioned		√	√	√	√	√	√	√	√		√	√			√			√					
Heat Gains	Included	√		√		√			√	√	√			√	√		√	√		√	√	√	√	√
	Not mentioned		√		√		√	√				√	√			√			√					
Technique	Cross ventilation	√	√		√	√				√						√	√							√
	Single sided ventilation		√	√												√	√							√
	Night ventilation										√				√	√	√	√					√	√
	Solar chimney																		√	√	√			√
	Wind catcher											√	√	√ PDEC									√	√
	Free running						√	√	√									√				√		√
Results	Improve natural ventilation	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	Energy savings	√			√	√		√	√	√	√			√	√	√	√	√	√	√	√	√	√	√

*: All elements have been insulated

**: Only opaque elements have been insulated

Table 7.1: Case studies and their results

7.1 Cross ventilation and single sided ventilation

The factors and elements that will be introduced into a model or study may differ, but how differently ventilation strategy behaves show uniformity in its results. A study conducted at the Polytechnic School of Valencia showed that even the position of the window could affect the effectiveness of cross ventilation (Mora-Pérez et al., 2016). Specifically, a student dormitory model (surface: $70m^2$) consisting of six different windows on opposite sides, was placed in the courtyard of the university. The prevailing climatic conditions are Mediterranean and the dominant annual wind direction (East-North-East) was taken into account. Perez and his team attempted to improve the building's natural ventilation capability by simulating various scenarios. Each scenario was dependent on the window's location, which had specific dimensions, on the east side of the building. This intervention, with proper installation, improved natural ventilation by 9.77% and reduce the cooling energy of the model consumed by 4.12%.

This occurs because the window was placed almost perpendicular to the wind direction and exploiting the increased pressure on this side. This exploitation and the reduced pressure on opposite sides increased the introduced air. Moreover, it was proved in another research carried out in India the same result. In this study, Visagavel and Srinivason (Visagavel & Srinivasan, 2009) studied the natural ventilation potential in a room of $9\ m^2$ and a height of 2.4 m. After determined the climate conditions in their model, they have studied three scenarios. In the first scenario, an opening was placed on the windward side of the building, on a single-sided façade. The second scenario was almost the same with the only difference that the window was placed on the leeward side of the building. In the third and last scenario, two openings were designed on opposite sides, one on the windward side and one on the leeward side of the building, creating cross ventilation. They observed that for the first two scenarios, when the window was placed on the windward side, it showed much better results than the leeward side. More precisely, the wind velocity on the leeward side was so low, almost imperceptible. On the other side, on the windward side, the results were at an adequate level. In the case of cross-ventilation, the highest speeds were exhibited. The cooperation of the frames allowed the entrance and exit of air without large losses of speeds and change of directions, in case of cross ventilation. Also, increasing the opening area in both the first and third scenarios improved the air velocity. The reason is that the air has a larger inlet area to move without significantly changing its speed by colliding on obstacles. Especially in the case of the first scenario, since the larger the opening, the easier the amount of incoming air can be separated from the outgoing air. This exploitation of separation becomes more exploitable in the case of the buoyance driven effect.

In Boston (Allocca et al., 2003), an interesting study was conducted on how the surface of the windows and their placement on the facade can affect the efficiency of natural ventilation. A 13.7 m^2 student room was designed to explore buoyance and wind-driven in unilateral window placement. Two scenarios were studied, one was to investigate the most effective window design and the second scenario was about the behavior of the best design option in the case of combined buoyance and wind-driven ventilation. For the first scenario, two designs were made, in the first design two windows were placed one on the upper side of the facade and one on the lower side, while in the second design a large window was placed. The results showed that the collaboration of the two windows, at different altitudes, operate better than the large frame. This occurs because the buoyance driven effect have more freely space to create better airflow. Cold air enters from the lower window and the hot air leaves from the higher opening. The conclusion from the second scenario is that openings located at different heights, the buoyance driven phenomenon dominates the air movement when the outside air is at low velocities. However, as the outdoor air increases in speed, the efficiency of the buoyance driven effect decreases, and the efficiency of the wind-driven increases. This result makes sense because the motion of air by pressure difference is stronger than the temperature difference, as was mentioned in previous chapters. Moreover, these two techniques are the principle design in order to cooling down the internal space of a building. It is important to consider other parameters that can aid to improve the indoor conditions. In the next paragraph will be described the night ventilation as one of the most effective strategy to decrease the cooling loads of a residential building.

Night ventilation

In previous paragraph, cross ventilation and single sided ventilation are the main techniques that are used to attain energy savings. Cooling loads are increased enough in period with high temperatures. In the summer period, solar radiation should be prevented as much as possible. A combination with natural ventilation at satisfactory levels can maintain the thermal comfort of the indoor environment. The renewal of the air internally is very important.

During the summer months the needs for cooling air is greater. However, in daytimes, the air temperatures during these months are largely quite high. As a result, the efficiency of natural ventilation is not so efficient. What has been observed is that in most areas and climates at night the air temperature drops considerably. This air can be exploited to maintain thermal comfort in the space. The study by (Gagliano et al., 2016b) examined the benefits of night ventilation, which can offer in relation to the building's energy efficiency. The object of study was a traditional residential building in Catania, Italy. In this building they have attempted to make some interventions but they had some limits because its architecture tempo. The building had high levels of thermal mass. Taking into account the thermal mass of the building and changing the air speed at night (1ACH, 2ACH, 3ACH), various scenarios were simulated. They observed that as the air velocity increased, the cooling energy decreased. In final scenario, they have attained up to 31% cooling energy reduction. A similar result was achieved in the Santamouris' study (M. Santamouris et al., 2010). They studied the effectiveness of night cooling would have on 214 houses with various area (55 to 480m^2). In this study, five different ventilation speeds were tested (2, 5, 10, 20, 30 ACH). The results showed that the higher the air velocity is, the greater the energy savings for cooling were achieved. Such a strategy can achieve a reduction from 10% to 40% respectively. The implementation of night ventilation improve the indoor conditions, because the external air with low temperature replace the indoor air with high temperature. Therefore, the low-temperature air relieves the elements from the excess heat storage, which otherwise would keep the internal temperature at high levels during the occupied hours. This decrease is not only due to the low temperatures and airflow rate, but also to the cooperation of the thermal mass during the day.

Thermal mass

As was previously mentions, night ventilation does not contribute to the passive cooling by the exploitation of low-temperature air, but also with the collaboration of thermal mass of the building elements.

Various studies have shown that the thermal mass of the building elements can improve or hinder the performance of night cooling. For example, in the study conducted by Geros (Geros et al., 1999) on three different office buildings, it was shown that the thermal mass of the building contributed significantly to the energy performance of the building, apart from the combination of various air velocities. Building that had high thermal mass, the reduction was caused from 39% to 96% (30ACH, 29ºC) depending on the wind speed and the setpoint temperature. As for the building with low thermal mass, the maximum reduction was 71% for a wind speed of 30 ACH and a temperature of 29ºC. The same is proved by the study of Calcerano and his team (F. Calcerano et al., 2017). They studied the influence of the thermal mass of a residential building in various locations of Italy, by testing six different ventilation strategies. The results indicated that regardless of the technique is used, the building with high thermal mass improves more night ventilation than from low thermal mass. This difference is due to the fact that during the day the elements of the building absorb thermal energy. When the system of the interior of the building comes into balance between the internal temperature and the temperature of the building then the elements start to emit heat. As a result, the interior of the building is maintained more at temperatures that are uncomfortable. What the engineer must achieve is to delay the time shift, also known as time lag. To do this it must have the highest possible heat capacity of the elements to store large amounts of thermal energy during the summer. When the day comes into an end the elements of the building will have to discharge all this thermal energy. At this point, the application of night ventilation takes place, which has proved above, with low ambient temperatures contributes to discharge these elements. It should be noted that buildings with very high thermal mass could be a problem because the discharge time during the night would not be enough. As a result, the interior of the building remains warm the next day.

The problem with this technique is the security of the building during its operation. At night, some windows should be left opened to allow outside cool air to enter and expelled warm air. There are two techniques mentioned in previous chapters that can provide a safety system and proper operation. One is the application of a thermal chimney in the building and the other is the application is wind catcher.

Solar chimney

Analyzing the first technique, its application requires proper design to perform properly. This means that various parameters must be studied. Each parameter has its own contribution to the system. The efficiency of the solar chimney is mainly due to the height, the gap width, the construction materials and the orientation. A study conducted by Koronaki (Koronaki, 2013) showed that these factors are crucial to system performance. In more detail, she studied three different constructions of solar chimneys in Athens. In her effort to find the ideal construction solar chimney for specific climate, she investigated various parameters. The parameters, that were examined, were the type of glass, height, width of the gap and orientation. The conclusion was that the west orientation solar chimney could produce up to 98% higher airflow than one that is south orientation. This can be attributed to the fact that the solar chimney oriented to the west, mainly in Greece, receives solar radiation for more hours compared to the south. In addition, the use of the materials had each own contribution to the solar chimney performance. Materials with satisfactory thermal mass and their high absorption capacity aid in its efficiency (Patou, 2013). In addition to the characteristics of the solar chimney, solar radiation as mentioned above is a factor that is influenced by the environment. Generally, the higher solar radiation solar chimney receives, the more intense is the buoyance driven effect and the more the airflow increases. Countries with high levels of solar radiation thrives on the use of solar chimneys in buildings. In the study (Zha et al., 2017a) found that increasing the solar radiation from 5W/m^2 to 600W/m^2 had an increase in air velocity from 0.02 m/s^2 to 0.45 m/s^2. These variations of solar radiation attain energy savings of up to 12.9% annually and 14.5% for the cooling period for the understudy building. The whole process of the solar chimney based on the buoyance driven effect. Thus, the more solar heat it receives and stores through the materials, the more efficient it would be. In this way, the air is getting warm enough at the point, for the exposed area of the solar chimney, at which moves upwards at a higher rate. As a result, this rate ensures adequate ventilation both during the day and at night. However, this rate is also determined by the inlet opening at the bottom of the solar chimney. In the research of Patou (Patou, 2013) was attempted to investigate this phenomenon in a 30m^2 residential building model. Essentially, he studied six different intersection inputs and outputs. The results were as expected. It was proved that as area increases, the volume of air flowing through the chimney increases too. The final area was at 0.09 m². Besides, this area was used in the solar chimney studied by Calcerano (Calcerano, 2017) in a 56 m² house in various locations of Italy.

The conclusion is that the solar chimney is a technique that has been extensively studied in recent years as a means of passive ventilation system, as explained in the chapter of solar chimney. Nevertheless, at the end of the previous paragraph, there is another technique that works in a similar way but can also take advantage of the wind driven effect. This is the wind catcher chimney.

Cooling tower

The next technique, as was mentioned, is wind catcher. In the previous chapter referred to various types of wind catcher and the operation of such a system. This type of system has the capability to either take the advantage of wind-driven effect or the buoyancy-driven effect.

In most cases, it is used to take the advantage of wind-driven. In this case, the chimney is oriented at the annual prevailing wind direction. Hence, the introduced air enters through the chimney and pressurizes the internal air. The internal air exits through the openings or the same chimney or from other chimney which are oriented at the leeward side. According to Hughes (Hughes & Mak, 2011) when the wind catcher operates by using wind-driven effect can increase the introduced air velocity by 76% while with the buoyance-driven effect by 47%. Zhe Ji and his colleagues (Adey et al., 2019) conducted a study on a real two storey office building in seven different locations of China. The study investigated four different scenarios. The first two scenarios were for use of only wind catchers but the wind speed was changing. As for the other two scenarios, top-hung windows were added and the wind speed was changing also. The results showed that using only wind catcher could lead up to 64% depending on the climatic conditions. When the wind catchers was combined with top-hung windows, this reduction climbed up to 78%. In regions where the wind speed was very low the energy savings was not significant compare to the region with high air velocity regions. The wind velocity has an important role for wind catcher's performance. Otherwise, the hot air will not be able to escape easily from the chimney, because wind catcher chimney does not have the same structure as solar chimney. Wind catcher chimney is more light structure in many cases louvres were used to prevent any object to get inside. The interesting here that if the louvres are not inclined correctly the wind catcher want operate correctly. The answer of the question, in what inclination louvres should be in order to operate optimal, is given by the study of Ben Richard Hughes and Abdul Ghani Sheffield (Hughes & Ghani, 2010). The study took place on a commercial building and they evaluated different inclination for wind catcher's louvre, from 10^o to 45^o with a step of 5^o. They concluded that a tilt of 35^o would be an optimal position for the louvres and the 40^o is the stall angle. At the optimal inclination the occupant's comfort has improved by 45%. The key is the different pressures that occur around the wind catcher, which lead the air to enter. Except for the inclination of the louvres, the height has its role to the wind tower performance.

A wind tower does not be made only with louvres, but also with an opening or openings to introduce fresh outdoor air into the internal space. Then, the height will determine the pressure difference in order to operate (Gage & Graham, 2000). According to McCabe and Roaf (McCabe & Roaf, 2013) an increase of 33% wind tower height can increase the flow rate of the system significantly. Apart from the height, the cross-section area also gives different results. In the same study (McCabe & Roaf, 2013), they increased or decreased by 50% the cross section area. They concluded that the increase led to a reduction of the air velocity, but the reduction of cross area increased the airflow into the indoor environment.

Another option of wind tower is the evaporative cooling tower. As it is described in the paragraph for the wind tower, there are different types of evaporative cooling techniques. Today the most used for the modern houses is the sprinkle water system. A hydraulic system is integrated with wind tower and sprays water. The outdoor hot air obtains wet bulb temperature and flows inside the room. Babich and his colleagues (Babich et al., 2017) investigated an evaporative cooling tower integrated on a residential building. The results was much promising, especially to a climate as Greece, because the system provokes a reduction of cooling energy between 35% and 52%, depending on the European country. This occurs because wet buld temperature is always lower than dry buld temperature, thus a cooler air takes place of the warmer air, which exits from the windows.

In both structures, the wind velocity and direction is affected not only by the climate conditions of each region but also from the surrounding obstacles. As it was mentions in paragraph for surroundings, they can affect significantly the wind behavior and thus the overall effectiveness of natural ventilation.

Surrounding obstacles

Except for the strategies, other characteristics of each region can influence the natural ventilation potential, because the air is affected. The condition of the air before reaches the understudy building is also important. Surrounding buildings are also those that can significantly affect the efficiency of natural ventilation.

The studies of Simuel Liu et al.(Liu et al., 2014) and AbdelRahman (AbdelRahman et al., 2017b) at which they studied various factors that may affect natural ventilation, one of which was the impact of neighboring buildings. These two studies have concluded the same results that the distance between neighboring buildings affects either positively or negatively the wind velocity and direction. In particular, wind velocity was higher when the distance between buildings was greater. Similarly, the direction did not change when the buildings between them were larger. This result makes sense because when the buildings were farther apart, air particles could move more easily. The reason is that the surrounding buildings affect the various pressures that are created around them. The farther away the buildings are, the less they affect the pressure differences. This is why an engineer needs to consider the surrounding obstacles in his/ her natural ventilation case study as a passive cooling technique.

Apart from the surrounding obstacles, it is proved that the orientation of the building relative to the prevailed wind direction can alternate the capability of the air to penetrate the internal space.

Orientation

The above studies showed that the distance between buildings significantly affects the efficiency of natural ventilation. Except for the distance, the orientation of the building also affects the proportion of natural ventilation exploitation inside the building. James Rilatupa's study (Rilatupa, 2019), in which a real 12.96 m^2 house model had been used, investigated the way that orientation can affect the effectiveness of natural ventilation. Various measuring instruments have been used for the progress of the experiment. The various factors studied were air temperature, air humidity, and air velocity relative to orientation and different times during a day. The results showed that each orientation at each different time has provided the building with different levels of temperature, humidity, and air velocity. More analytically, it was observed that when the building was oriented north-south, in the morning (08:30), the temperature ranged from 30 - 32.8ºC while for west-east, northeast-southwest, and southeast-northwest the temperatures fluctuated from 28 to 31.6ºC. At 12:30, it was observed that for all orientations the air temperature had in-creased with the lowest values being presented in the east-west orientation (35.0-38.7ºC), while the highest was observed in the north-south orientation 36.9-39.4ºC. While at 17:00 in respectively the above orientations, the extreme values were respectively 31.0-37.7ºC and 36.0-38.0ºC. The other parameters are affected in the same way. In this study, it was proved that the best orientation was east-west for the lowest temperature and humidity, while for the wind speed it was southeast-northwest. As shown in this study to obtain the best efficiency of natural ventilation is not an easy task. These differences usually occur because each orientation is exposed to different percentages of solar radiation. Furthermore, the main direction of the air, the air velocity, and the surrounding buildings or vegetation can significantly affect the three studied parameters above.

Nie and his colleagues (Nie et al., 2015) demonstrate these differences in both the amount of solar radiation entering the building and the main direction over time in the study. In this study, a 120m^2 detached residential building has been examined in various types of orientation regarding its energy efficiency and the efficiency of natural ventilation. After finding the best combination of openings to attain the maximum possible ventilation rate in the space, they investigated the orientation effect. According to their research, in the location where they have studied the building, the best orientation was the west. What they have done, they find out which air direction was blowing more frequently annually and they pivoted the building. Consequently, they attained the maximum air movement in space. Nevertheless, they noticed that the energy consumption of the building in this orientation had reached its maximum value. Therefore, they needed to find the intersection where they would exploit the benefits of ventilation and the lowest possible cooling energy consumption. The orientation found was between south and north. The conclusion reached from this study was that the best efficiency of natural ventilation maybe burdened the energy efficiency of the building. Hence, the engineer will have to find the intersection of these two.

As it seems, orientation has its impact to the overall energy performance of the under-study building. However, climatic conditions can make significant changes in the design stage of a building to exploit natural ventilation to reduce cooling loads.

Climate

The orientation is influenced by the prevailed climate in the area where a building is being studied. A study (Haase & Amato, 2009) conducted in different parts of China showed that climate can affect the orientation of the building. Specifically, a model residential building was studied and placed in 12 different areas of China. The climates, that were examined, were tropical, subtropical, and temperate climates. The research was executed in the summer period. The results showed that in the tropical climate the best orientation was between 150° and 188° with a probability of natural ventilation of 36% to 50%. This percentage achieves an improvement in the thermal comfort of internal space between 9% and 41%. For the subtropical climate, the respective values are for orientation 322.5° and 192.5°, natural ventilation 18% to 29%, and improvement of thermal comfort 3% to 14%. For mild climates, the corresponding values are, orientation from 170° to 177.5°, natural ventilation 12% to 14%, and improvement of thermal comfort due to ventilation 8% to 56%. The improvements were obtained because the intersection of the natural ventilation and the energy consumption of the building was achieved or satisfied regarding the climate and the corresponding orientation.

These two factors, climatic conditions and orientation, are not the only ones that were proved that affect natural ventilation performance. Window wall ratio is the one that determines the amount of volume air which will penetrate in the indoor environment.

Window Wall Ratio (WWR)

Climatic conditions are the main parameter, which can determine in large percentage the natural ventilation potential. On the other hand, windows have their contribution to improve natural ventilation performance. The size of the windows, as it is analyzed at the beginning of this chapter, in most case are those, which determine the airflow rate. In case study of Aldawoud (Aldawoud, 2017) different percentage of inlet and outlet window wall ratio was examined. He observed when the windward side high-pressure windows are in greater percentage than the windows of leeward side, the airflow rate appeared with higher values and the profit from this strategy was an energy savings about 33%. The reason is that the windward side windows introduce larger air volume and because of the smaller surface of the leeward side the airflow increases at this side (Bernoulli Effect). Nevertheless, this percentage should not be too high because then other problems are created. In case of Chiesa et al (Chiesa et al., 2019) in which they studied an office building and its performance relative to various WWR values. It was observed that after specific point of window wall ratio the energy needs were initiated to increase. The reason was that the percentage of solar radiation penetrating the interior space increased along with the increase of the windows' area. On one hand, it is beneficial on winter period but on the other hand on summer period increases dramatically the cooling needs. Hence, it is important to be done an investigation detailed enough to determine the WWR at the design stage. In a point that the natural ventilation and solar radiation are benefit the energy performance of the building. For instance, an office building in different European countries was examined the optimal WWR in order to improve the energy performance of the building. The results showed that Northern Europe need higher WWR compare to Southern Europe (Goia, 2016). The variations of WWR are relative to the angle of the sun in relation of earth's angle.

7.2 OVERVIEW OF THE RESULTS

To conclude, all strategies are profitable under specific conditions, because each strategy is affected differently. As was mentioned, cross ventilation and single-sided ventilation are benefited differently from buoyance driven or wind-driven. In most cases, cross ventilation is benefited more by wind-driven than buoyance driven and vice versa for single-sided ventilation. In both cases, the design properties will determine which driven type will dominate. For instance, in the location where the wind velocities are very low, buoyance driven operated better for single-sided with two separated windows than cross ventilation (Gratia et al., 2004). Except for that, depending on the time during the day, the effectiveness of natural ventilation can be increased or decreased.

Night ventilation was proved the most profitable because at these times period occupants can exploit the cooling capacity of natural ventilation better. That occurs because in nighttime air temperature obtain low temperature enough to cool down the building elements and internal space. Hence, in morning times building provide a more pleasant indoor environment for the occupants. The ability of night ventilation is not supported only by the air temperature but also the thermal mass of the building.

Buildings with high thermal mass were proven more suitable with night ventilation than low thermal mass. The element heat storage capacity, during the day, determines the time lag in which the indoor temperature will overpass the thermal comfort limits. The problem with night ventilation is security.

Two structures can provide natural ventilation and security into the building. Solar chimneys and cooling towers are these structures. A solar chimney can minimize the cooling loads of a building by exploiting the buoyance driven effect. The higher solar radiation is, the higher the airflow rate is obtained and more air exits from the solar chimney. The problem starts when there isn't any solar radiation, in case of a cloudy day. The buoyance-driven effect isn't so intensive and thus solar chimney does not operate so efficiently. Except for that, the height, the width of gap and solar absorbance affect the effectiveness of the solar chimney. Moreover, on windy days a solar chimney again cannot exploit the wind-driven phenomenon. In this case, a wind catcher or cooling tower could be more suitable to cool the building.

A cooling tower can use both wind-driven and buoyance driven but not so effective in case of buoyance effect. They are many types of wind catcher depending on the openings and the use of louvers or not. Wind catcher introduces air from the top to its bottom and thus reduce the cooling energy consumption. It is important for the opening to be oriented at the prevailed wind. Apart from that, an integration of a water supply system with sprinkles or wet walls or wet curtains can achieve lower air temperatures. Specifically, the air obtains wet bulb temperature and then enters into the indoor environment and thus cooling the space. This system was proven more beneficial than the traditional cooling tower. All these strategies are affected greatly from the surrounding obstacles, orientation of the building, climate and WWR.

Surrounding obstacles, as was mentions, can affect the wind velocity and direction. As it is proved, the identification of the surrounding obstacles can alternate the natural ventilation potential inside the building. The greater the distance is, the higher wind velocity introduce in the internal space and not changing noticeably the direction of it. Hence, it is important to keep buildings in distance.

Except for that, the orientation can aid to introduce more air volume, but it must be considered the energy performance of the building which can be affected by other factors. A wrong orientation can lead to higher cooling energy consumption than lower by implementing natural ventilation. Orientation and surrounding obstacles are some of the parameters that affect wind velocity and direction.

Climatic conditions are those which determine the natural ventilation from scratch. All factors are critically affected by the prevail climate of the understudy region. In Mediterranean climate and region with similar climate are benefited enough from passive cooling technique to attain energy savings.

Apart from that window to wall ratio can affect natural ventilation significantly, as it was shown above. The WWR determines the air volume which will penetrates the indoor space and the solar radiation too. The performance of solar chimney and wind catcher are also affected by WWR. Both of them are using, in most cases, the external windows as inlet or outlet respectively. Thus, the order and rationality to design a passive cooling technique can be a difficult task, but if someone comprehend, how all these systems operate and how the air flows then he/she is in a position to implement such techniques.

8 Conclusion

In this dissertation, the natural ventilation in the buildings was analyzed as a means of cooling. In general, as discussed in Chapter Two, new buildings should consume as low energy as possible. The rest of the energy must be produced by renewable energy sources. In recent years, low-energy residential buildings in Europe are growing. After the implementation of the European Directive 2010/31 / EU for the achievement of target 20/20/20, an increase of such buildings is observed in Greece also. However, in order to achieve low energy consumption, the use of active systems should be minimized and a large percentage of passive systems should be applied. As described the appearance of passive buildings paved the way in this direction. These buildings largely use passive systems. There are various ways to use passive systems, for example, shading devices, high-performance frames, high-performance insulation materials, natural ventilation, etc. Natural ventilation is one of these methods that was analyzed.

Natural ventilation has the ability to remove indoor air, which carries in its mass at high levels of humidity, CO2, and temperature in summer. This air is replaced by fresh air that has a lower temperature, lower humidity levels, and more quantity of oxygen. In this dissertation, natural ventilation was mainly studied as a means of cooling the building, so its application has to do mainly with the removal of the extra heat. The two drive forces, wind driven and buoyance driven, are responsible for the movement of the outdoor air into the interior space and vise versa. Wind driven is created by the pressure differences between the windward side and the leeward side. As for the buoyance driven is occurred by the temperature differences, because of the temperature stratification in the indoor room. As it seems, both happen simultaneously, but the intensity of each determines its performance and prevalence.

These two factors are the principal factors to comprehend the functionality of passive cooling strategies. The strategies that were analyzed were the most used and common. Cross ventilation, which in most cases uses the wind-driven effect, showed very promising results. Moreover, cross ventilation is more suitable for a detached residential building than on a multi-family building. For flat or rooms, single-sided ventilation is more commonly used than cross ventilation, because of the plan restrictions. Both have pros and cons. Cross ventilation is more suitable for regions where the wind velocity is at a high rate. Besides, the rate can be increased by the area differential of the openings between the windward side and leeward side. The problem with cross ventilation is that low or zero wind velocity cannot operate well enough. In contrast, single-sided ventilation with two windows at different heights can reduce cooling loads significantly. Almost the same results were observed in the case of a large window. It must be underlined that these openings must face at the windward side. The drawbacks of the single-sided ventilation are that the airflow rate achieves very low speeds and cannot be benefited by the high wind velocities. Cross and single sided ventilation can be used any time of the day. Especially, at nighttime both ventilation types can be improved by night ventilation.

Night ventilation takes the advantage of low ambient air temperature and cools down the internal space of the building. Compare to day ventilation, night ventilation indicates better results and aid to obtain cooler indoor temperature at morning times. The disadvantage of such implementation are security restrictions and it must be careful applied not to overcool the indoor space during night. The security issue can be solved by two devices solar chimney and wind tower.

These two different devices could aid to maintain the thermal comfort of the building in more secure way. Besides, they can be used to adjust the indoor temperature not to overcool it. Solar chimney takes the advantage of buoyance driven effect. The structure and the material that are used determines in a significant degree its performance. The height, the gap width, inclination (for exclusive cases) and orientation can affect the performance of it. Height affects the operation capability more than gap width, because the buoyance driven effect is affected by the stratification. On the other hand, inclination and orientation determines the amount of solar radiation reaches on solar chimney receive surface. It was shown that an inclination of 20^{o} could improve the received solar radiation amount. Moreover, the most used orientation in many study cases were south and west orientation, which can be more profitable for solar chimney in Mediterranean countries. The disadvantages of solar chimney are the space that it needs and the height which can be restricted by local legislation. Another problem, in cloudy days or rainy days does not operates or operates with very low contribution level. These disadvantage are not for wind catcher devices.

Wind tower contributes for the cooling energy reduction differently from solar chimney. The main driven effect for wind tower is wind driven. A one sided chimney facing the prevail wing direction. Therefore, the high pressure that occurred on the windward side of the chimney forces the air to follow a downward direction, distributed into the conditioned space and exits from windows on leeward sides. As it is mentioned in chapter three, they are many-sided chimneys. The most used are one sided, two sided and four sided (mostly in Middle East). Wind catcher was proved a significant device to reduce cooling energy consumption. Apart from the classic wind tower, there is another architecture design which combines evaporative cooling technique. Wet curtains or wet walls or sprinkles water pump are integrated in wind tower chimney and thus cooling down the hot air, which is heavier and follows downward direction. This upgrade showed a significant reduction of cooling energy more that the simple wind tower. The disadvantage of wind tower is that in no wind regions does not work properly and some cases can introduce hot air. These problems can be solved with the evaporative cooling techniques, but the main problems with this technique are water consumption and increases humidity.

Other factors influence natural ventilation are thermal mass, window wall ratio, surrounding obstacles, orientation of the building and climate conditions. Beginning with thermal mass, which depends on the thermal capacity of structure materials. Concrete, bricks and tiles are materials with high thermal storage capability. Various surveys concluded that residential buildings with high thermal mass could be benefited from natural ventilation more than those with low thermal mass. Thermal mass combined with night ventilation can achieve a significant reduction of cooling energy consumption. Therefore, it is essential for residential buildings to have thermal mass enough to take advantage of natural ventilation.

On the other hand, window wall ratio has its own footprint in the energy building performance. As it was analyzed, the wider the windows the more air introduction occurs. The main problem is that the larger the opening surface increases heat gains and these in turn increases the internal temperature. Hence, it is vital to locate the best ratio for each façade. In Mediterranean regions, a 20-40% of WWR for all orientation was proved optimum for natural ventilation and solar radiation restriction.

Another factor is the surrounding obstacles in the region of the understudy building. Neighboring buildings may not allow good level of ventilation as the above case indicate. It was observed that the more, closer the surroundings obstacles are the more wind direction is affected, and the more wind velocity values is obtaining. Thus, it is important to have enough surrounding space in order to allow high wind velocities and the wind direction not change enough from what the designer expects.

Orientation is another factor that affects natural ventilation potential. In Mediterranean location, south north orientation is the most common use. The problem is that this orientation is according to the solar radiation minimization. Therefore, wind direction and solar radiation should be taken into account simultaneously to be benefited from both.

The final factor is the climate conditions. Many studied have been carried out relative to various climate conditions. In most climates, natural ventilation showed a good behavior to obtain thermal comfort and reduce the energy consumption of a residential building. Mediterranean climate, in all cases, natural ventilation can improve the energy consumption of a building. Thus, it is considered necessary to use natural ventilation for the summer period in this climate.

All the above techniques and parameters can contribute either positively or negatively to cooling energy reduction by applying them in various ways. Nevertheless, before the final decision and implementation, it is required to simulate different scenarios by the use of special software. EnergyPlus and CFD simulation are some of the most powerful software that are commonly used for such calculations. As it was described, EnergyPlus has not the same capabilities as CFD simulation and vice versa. After analyzing each methodology, which is applied in order to simulate a model, different results are exported from each software. EnergyPlus is used for accurate calculations of energy consumption (annually or monthly or daily). In contrast, CFD simulation is used fluid calculations which are the wind direction and velocity and temperature stratification of the boundary system with specific inputs. Hence, if someone attempts to implement these software, it is recommended to coupled them to obtain more realistic results in case of natural ventilation. The results from different cases indicated that coupling both EnergyPlus and CFD simulation provide the user with more accurate results. EnergyPlus is capable to simulate natural ventilation cases but it gives only “a part of the big picture”. Overall, the methodology that must be followed for both is more or less the same but the inputs insights are these, which differ.

Most of the case studies that were investigated in this dissertation were carried out mainly using EnergyPlus software. Some case studies were analyzed even if they used different software. The main climatic condition was the Mediterranean climate, but some regions that were included have close enough the same conditions. The use of studies with different climate and software contribute to comprehend the various passive cooling techniques. Case studies that were included, carried out in Italy, Spain, South Africa, Middle East, China, and limited studies in Greece. All these cases contribute to the final decision. Greece, as it was described, has a typical Mediterranean climate with a high percentage of sunny and windy days annually. Therefore, studies that have as an object same climatic conditions are favorable to be implemented and in Greece. Starting with the cross and single-sided ventilation, implementation of such a technique could reduce the cooling energy demand up to 90% and 4% more if these techniques combined with night ventilation and high thermal mass. As for the solar chimney technique, a reduction of 30% can be achieved, when the buoyance driven effect is intensive. In the case of a wind tower, this reduction could climb up to 50% if it is combined with the evaporative cooling technique. Otherwise, the reduction stays the same at up to 30%.

Generally, Greek Climate natural ventilation techniques is very promising to be implemented in Greek residential buildings. In many surveys were proven that many benefits can be attained by the passive cooling techniques in terms of thermal comfort and energy savings.

The literature review indicated that further research is needed in the field of buildings natural ventilation. Especially, significant gaps and limitations have been observed as regards the studies which are referred to residential buildings located in areas with a Mediterranean climate and more specifically in Greece. In this context, future research could pay attention to the following issues. Initially, many studies do not take into account the surrounding buildings. Hence, it is essential for surrounding buildings to be included in future studies for natural ventilation performance and energy performance. Secondly, the surrounding vegetation and its contribution to the energy performance of a residential building via natural ventilation was not investigated enough. It is crucial to be studied simultaneously with the energy calculations of the residential building. Thirdly, wind catchers and PDEC need to be investigated more in residential buildings. Finally, lack was observed in relation to the WWR for Greek residential dwellings relative to better performance of natural ventilation. For this reason, it is important the ratio at which natural ventilation can be beneficial to the energy savings to be investigated.

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